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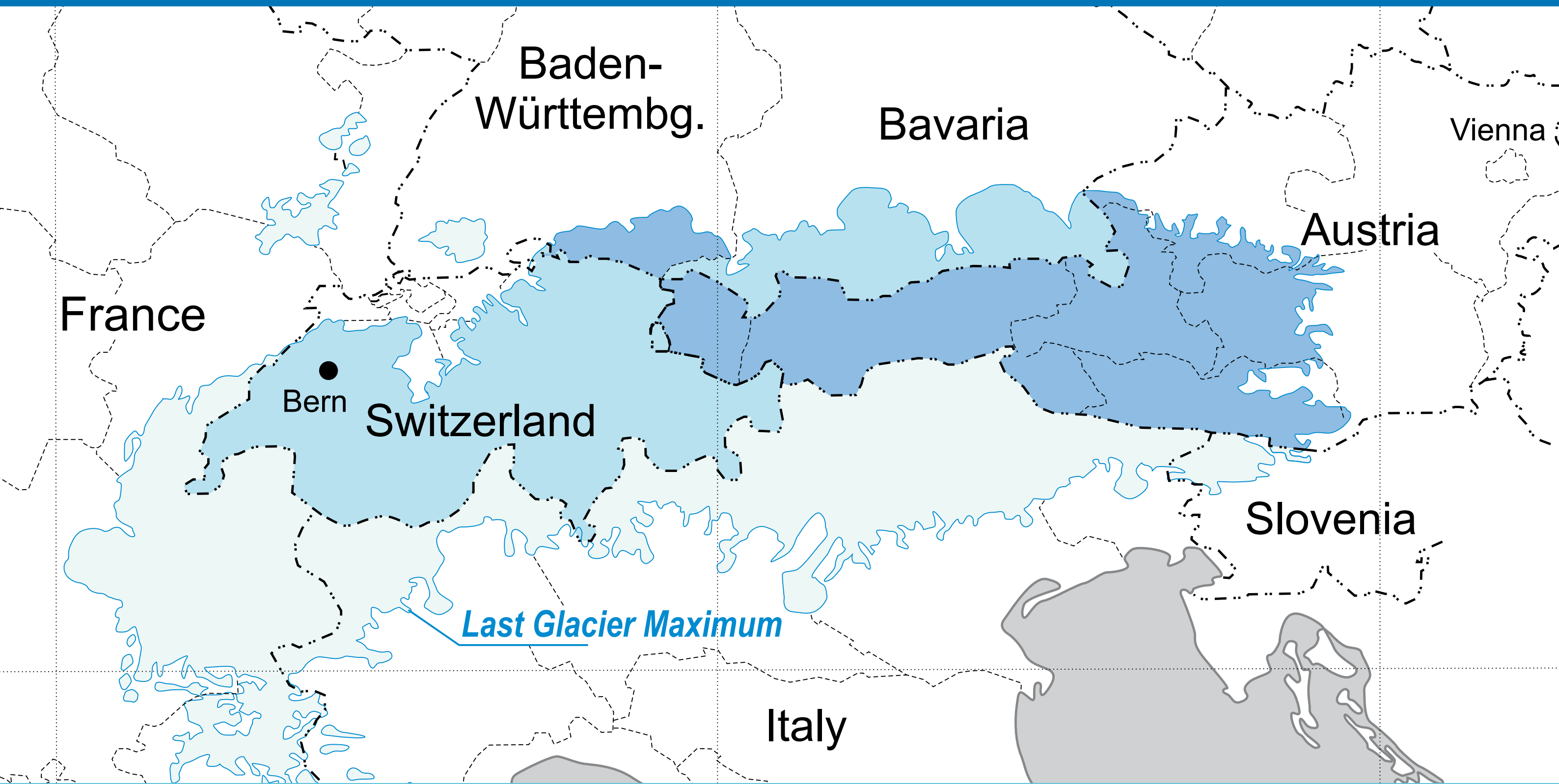

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GLACIATIONS AND PERIGLACIAL FEATURES IN CENTRAL EUROPE

SPECIAL ISSUE FOR THE XVIII INQUA CONGRESS IN BERN, SWITZERLAND

GUEST EDITORS

Margot Böse (DEUQUA – German Quaternary Association)

Markus Fiebig (AGAQ – Working Group on the Quaternary of the Alpine Foreland)

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COVER FIGURE
Markus Fiebig (AGAQ), The Alpine ice cap redrawn after Ehlers, J. & Gibbard, P. (2004)*

*Quaternary Glaciations Extent and Chronology Part I: Europe. Development in Quaternary Science 2, Elsevier (Amsterdam)

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Foreword

Hosting the XVIII INQUA Congress in Bern, Switzerland, is a great event and an honour for the Quaternary scientific community in Europe. Since the foundation of DEUQUA (German Quaternary Association) in 1948, close links have existed with our neighbouring countries, with members especially, but not only, from Austria and Switzerland. As the central European high mountain range, the Alps are a research object in all three countries and are thus of shared interest. For several decades, DEUQUA has also had board members from both countries who have repeatedly organised DEUQUA meetings in their respective countries. Switzerland hosted DEUQUA in Zurich in 1982 and in Bern in 2000; Austria was the host in Vienna in 1978 and 2008, and in Gmunden in 1996. Therefore we are pleased to present a volume of E&G Quaternary Science Journal for the participants of the INQUA Congress, with papers highlighting some aspects of Quaternary research in Germany, Austria, and Switzerland.

Germany is the only country affected by both the Scandinavian and the Alpine glaciations. The long tradition in research on the Quaternary glaciations started in the second half of the 18th century. Prominent Swiss researchers promoted the idea of an Alpine glaciation in the 18th and 19th century and already developed the idea of polyglacialism. It proved much more difficult to convey the idea of a glaciation – and therefore the glacial transport of boulders from Scandinavia to northern Germany – and to achieve the general acceptance of this hypothesis, as a possible glaciation was not as evident as in the Alps, where the glaciers were advancing during the Little Ice Age.

It was Albrecht Penck – first working in Saxony, then continuing his outstanding work in the Alps and the northern Alpine foreland after he became a professor in Vienna – who gave impulses in stratigraphy that are still considered today. Penck is one of the "fathers" of polyglacialism in the areas affected by the Scandinavian inland ice, though he did not create the terms Elster, Saale and Weichsel. But for the Alpine foreland, he introduced the terms Günz, Mindel, Riss and Würm for the glaciations. Although much research has refined this concept, the names are still used in the context of German, Austrian and Swiss alpine stratigraphy.

For the warm phases, palynology brought insights into the changing vegetation and therefore into palaeoenvironmental conditions during interglacials and interstadials.

In northern Germany, morphostratigraphy, lithostratigraphy and sedimentology were important methods for studying the formerly glaciated areas and revealed with time a more and more detailed view of Quaternary development and the related glacial processes. Those methods are still used to reconstruct and characterize processes forming the old morainic area (cf. Winsemann et al., this volume). Geochronological studies dating minerogenic deposits also of Middle Pleistocene age will probably help in future to specify these processes over time. In general, physical and chemical dating methods have already revised the idea of the time frame of the Quaternary, and are still refining in detail our knowledge about age estimates of processes and events. Examples of dating results for the last glacial cycle and evaluations of the methods employed are given by Reuther et al. and Lüthgens & Böse (this volume). The ongoing development and refinement of these methods will surely provide more and more high-resolution tools for interpreting the past, including the processes involved.

Periglacial conditions widely affected the non-glaciated areas during the glacial cycles and transformed their topography to a certain extent. Periglacial relicts such as landforms and sediments are still part of our present-day landscape. Apart from the small glaciated mountain peaks of the Harz, the Bavarian Forest and the Black Forest, the non-glaciated areas experienced repeated transformation and sedimentation caused by various periglacial processes. Especially the widespread loess deposits and the palaeosoils within them became a valuable archive for climatic reconstructions (cf. Terhorst et al., this volume).

The river systems and their terraces are mainly linked to repeated climatic changes during the glacial cycles. The terraces are impressive landforms in the present-day landscape; they can often be associated with the changing fluvial conditions and are also linked with loess archives.

Polyglaciation was the basis of all subsequent ideas and studies about palaeoclimatic changes. Such studies are abundant and of extremely great interest for the recent discussion of global change as reconstructing the past helps us to develop and understand the models of the future. For these studies, the analysis of terrestrial archives is essential as they offer an insight into the local variety of climate embedded in the global climate fluctuations.

The first part of the volume is dedicated to the northern glaciations and a loess area in Austria.

Research results from the archives in the Alpine foreland are presented in the second half of the volume by the AGAQ (Arbeitsgruppe Alpenvorland-Quartär – Working group on the Quaternary of the Alpine Foreland). It has been in existence for about 20 years as an informal working group mainly of DEUQUA members working on stratigraphical correlations.

Margot Böse
President of DEUQUA

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Depositional architecture and palaeogeographic significance of Middle Pleistocene glaciolacustrine ice marginal deposits in northwestern Germany: a synoptic overview

Jutta Winsemann, Christian Brandes, Ulrich Polom, Christian Weber

Abstract: Ice-marginal deposits are important palaeogeographic archives, recording the glacial history of sedimentary basins. This paper focuses on the sedimentary characteristics, depositional history and palaeogeographic significance of ice-marginal deposits in the Weserbergland and Leinebergland, which were deposited into deep proglacial lakes at the terminus of the Saalian Drenthe ice sheet. The depositional architecture and deformation patterns of ice-marginal deposits will be discussed with respect to glacier termini dynamics, lake-level fluctuations and basement tectonics. During the last 10 years, a total of 27 sand and gravel pits and more than 4000 borehole logs were evaluated in order to document the regional pattern and character of Middle Pleistocene ice-marginal deposits. The field study was supported with a shear-wave seismic survey. Based on this data set, and analysis of digital elevation models with geographic information systems (GIS), we attempt to improve earlier palaeogeographic reconstructions of glacial lakes in the Weserbergland and Leinebergland and reconcile some inconsistencies presented in the current valley-fill models. We hypothesize that the formation and catastrophic drainage of deep proglacial lakes in front of the Drenthe ice sheet considerably influenced the ice-sheet stability and may have initiated the Hondsrug ice stream and rapid deglaciation. Based on our analysis, it seems unlikely that the Elsterian ice sheet reached farther south than the Saalian Drenthe ice sheet in the study area.

[Faziesarchitektur und paläogeographische Bedeutung mittelpleistozäner glazilakustriner Eisrandsysteme in Nordwest-Deutschland: ein synoptischer Überblick]

Kurzfassung: Eisrandsysteme sind bedeutende paläogeographische Archive, die die Vereisungsgeschichte in marinen und kontinentalen Becken aufzeichnen. Im Fokus dieser Arbeit stehen saalezeitliche, glazilakustrine Eisrandablagerungen des Weser-und Leineberglandes, die in etwa die maximale Ausdehnung des saalezeitlichen Drenthe-Eisschildes markieren. Die Faziesarchitektur und die internen Deformationstrukturen dieser Eisrandablagerungen werden in Hinblick auf Gletscherdynamik, hochfrequente Seespiegelschwankungen und Basement-Tektonik diskutiert. In den letzen 10 Jahren haben wir im Weser- und Leinebergland 27 Kies- und Sandgruben neu bearbeitetet und mehr als 4000 Bohrungen ausgewertet, um die saalezeitliche Sedimentation im Bereich des Eisrandes und der vorgelagerten Seebecken zu rekonstruieren. Die Geländearbeiten wurden durch Scherwellenseismik-Profile ergänzt. Basierend auf diesen Daten wurden mit Hilfe von digitalen Höhenmodellen und geographischen Informationssystemen (GIS) saalezeitliche Eisstauseen im Weser- und Leinebergland rekonstruiert.
Wir vermuten, dass die Bildung und das katastrophale Auslaufen dieser tiefen Eisstausseen die Stabilität des drenthezeitlichen Eisschildes stark beeinflusst und möglicherweise den Hondsrug Eisstrom initiiert haben. Unsere Studie zeigt darüber hinaus, dass der elsterzeitliche Eisschild vermutlich nicht weiter als der drenthezeitliche Eisschild nach Süden vorgedrungen ist, als bisher angenommen wurde.

Keywords: *glacial Lake Weser, glacial Lake Leine, subaqueous ice-contact fans, ice-marginal deltas, normal faults, Saalian glaciation, Elsterian glaciation, Hondsrug ice stream, north west Germany*

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1 Introduction

In numerous places across central Europe, ice-marginal lakes formed due to the blocking of river systems by Pleistocene ice sheets (e.g., Eissmann 1997, 2002, Junge 1998). The blocking of the Upper Weser and Upper Leine Valley by the Saalian Drenthe ice sheet must have led to a disruption of the northward river drainage and the initiation of glacial lake formation. However, the existence and size of these glacial lakes has been controversial for about 100 years and various palaeogeographic reconstructions have been proposed. Reconstructions based on fine-grained lake bottom sediments in the northernmost part of the Upper Weser and Leine Valley indicate small and very shallow glacial lakes (e.g., Spethmann 1908, Feldmann 2002). In contrast, Thome (1983) and Klostermann (1992) argued that glacial lake Weser stood at a level of 300 m a.s.l., controlled by the altitudes of potential outlet channels and inferred water depth to be up to 250 m. More recent studies assume maximum lake levels of approximately 200 m a.s.l. for both glacial Lake Weser and glacial Lake Leine (Thome 1998, Winsemann et al. 2007b, 2009, 2011).

This long-term debate probably reflects problems recognizing short-lived lakes in steeper terrains. Compared to large ice-dammed lakes with long-lived stable water levels, smaller short-lived lakes are much more difficult to map because their shoreline features are commonly less well developed and less abundant. Although shoreline features have been reported from other high-relief lake areas

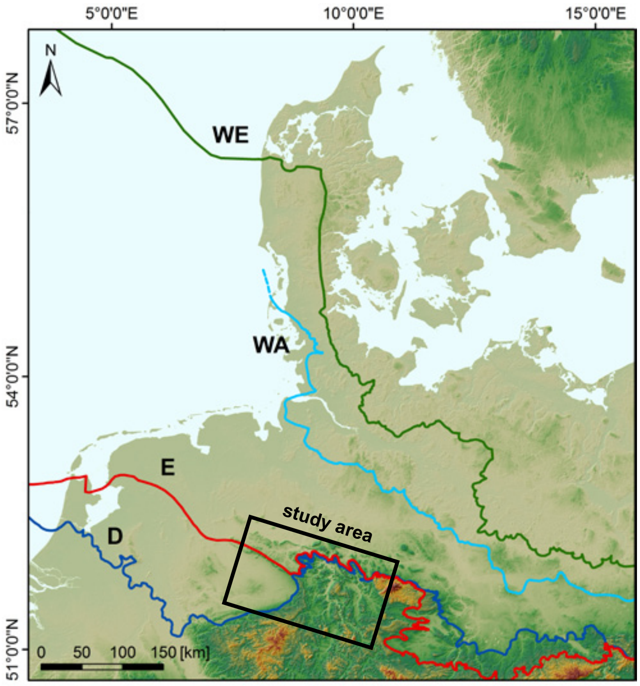

Fig. 1: Extent of the Pleistocene ice sheets in central Europe. E: Maximum extent of the Elsterian ice-margin. D: Maximum extent of the Saalian Drenthe ice-margin. WA: Maximum extent of the Saalian Warthe ice-margin. WE: Maximum extent of the Weichselian ice-margin. Modified after Ehlers *et al. (2004).*

Abb. 1: Ausdehnung der Pleistozänen Eisschilde in Mitteleuropa. E: Maximale Ausdehnung des elsterzeitlichen Eisschildes. D: Maximale Ausdehnung des saalezeitlichen Drenthe Eisschildes. WA: Maximale Ausdehnung des saalezeitlichen Warthe Eisschildes. WE: Maximale Ausdehnung des weichselzeitlichen Eisschildes. Verändert nach Ehlers *et al. (2004).*

(e.g., Carling et al. 2002, Johnsen & Brennand 2006) they are probably rare in steep short-lived glacial lakes, characterized by rapid lake-level fluctuations. After lake drainage these sparse shoreline features may be rapidly eroded by postglacial erosion (e.g., Colman et al. 1994, LaRoque, Dubois & Leblon 2003).

The study reported here focuses on the sedimentary characteristics, depositional history and palaeogeographic significance of glaciolacustrine ice-marginal deposits in the Upper Weser and Upper Leine Valley, which formed at the terminus of the Drenthe ice sheet. The objective is to provide a synthesis of the stratigraphic architecture of glaciolacustrine ice-marginal deposits. The depositional architecture and deformation patterns of these deposits will be discussed with respect to glacier termini dynamics, lake-level fluctuations and basement tectonics. We employ digital elevation models and geographic information systems (GIS) to improve earlier palaeogeographic reconstructions of glacial Lake Weser and glacial Lake Leine and attempt to reconcile some inconsistencies present in the current valley-fill models.

2 Study area and previous research

The study area is located in the Weserbergland and Leinebergland area south of the North German Lowlands (Fig. 1 and Fig. 2). The terrain is characterized by several mountain ridges up to 400 m high, mainly made up by Mesozoic sedimentary rocks and broad valleys of the River Weser and the River Leine. It is still under debate if the study area was affected by both the Elsterian and Saalian Drenthe glaciations. The reconstruction of the Elsterian ice margin is difficult because the sediments became overridden by the later Saalian ice sheet (e.g., Caspers et al. 1995). The Elsterian ice-margin probably terminated north of the Teutoburger Wald Mountains (Ehlers et al. 2004). Most reconstructions assume that ice lobes of the Elsterian ice sheet advanced into the Upper Weser and Leine Valleys (e.g., Liedtke 1981, Jordan 1989, Klostermann 1992, 1995, Thome 1998, Rohde & Thiem 1998, Feldmann 2002). This assumption is mainly based on the occurrence of scattered erratic clasts beyond the Saalian ice-margin (e.g., Waldeck 1975, Jordan 1994), the occurrence of reworked erratic clasts in middle Pleistocene fluvial deposits (e.g., Rohde & Thiem 1998) and the occurrence of what appears to be Elsterian till in boreholes near Bünde, Bad Salzuflen and Vlotho (Skupin, Speetzen & Zandstra 2003).

The maximum extent of the Saalian ice cover in northwest Germany was reached during the older Saalian Drenthe ice advance ("Drenthe-Zeitz Phase"; cf. Litt et al. 2007). Ice lobes of this ice sheet intruded into the Münsterland Embayment, the Upper Weser Valley and Upper Leine Valley, damming the drainage pathways of rivers (e.g., Thome 1983, 1998, Klostermann 1992, Herget 1998, Skupin, Speetzen & Zandstra 1993, 2003, Ehlers et al. 2004, Winsemann et al. 2007, 2009, Meinsen et al. in press). The second major ice advance of the Saalian glaciation (Warthian ice sheet) did not reach the study area (Fig. 1).

The blocking of the River Weser and River Leine Valley by the Drenthe ice sheet led to the formation of glacial lakes. The ice-dammed lake within the Upper Weser Valley is referred to as "glacial Lake Rinteln" (Spethmann, 1908), "glacial Lake Weserbergland" (Klostermann 1992, Thome 1998) or "glacial Lake Weser" (Winsemann et al. 2009). Glacial Lake Rinteln refers to the northernmost part of the Upper Weser Valley, named by Spethmann (1908) after the small town of Rinteln. As the lake mainly occupied the Upper Weser Valley, the name "glacial Lake Weser" is the most appropriate designation and we suggest the continued use of this name. The ice-dammed lake in the Leine valley is referred to as "glacial Lake Leine" (e.g., Thome 1998, Winsemann et al. 2007).

During the last 100 years, numerous studies have been carried out in the Upper Weser and Upper Leine Valley to reconstruct the former ice-margins and map economically important ice-marginal and fluvial deposits. Detailed geological mapping (1: 25 000) of the Upper Weser Valley and Upper Leine Valley started at the beginning of the 20th century (1900–1930) and continued in the 1970s, 1980s and 1990s. More detailed studies were based on landform and provenance analysis of Pleistocene ice-marginal deposits, resulting in various depositional models, commonly assuming a subaerial formation of ice-marginal deposits (e.g., Siegert 1912, 1921, Grupe 1926, 1930, Soergel 1921, Stach 1930, 1950, Lüttig 1954, 1958, 1960, Wortmann 1968, Seraphim 1972, 1973, Rausch, 1975, 1977, Bombien 1987, Wortmann & Wortmann 1987, Kaltwang 1992, Wellmann 1998, Feldmann 2002, Skupin, Speetzen & Zandstra 2003).

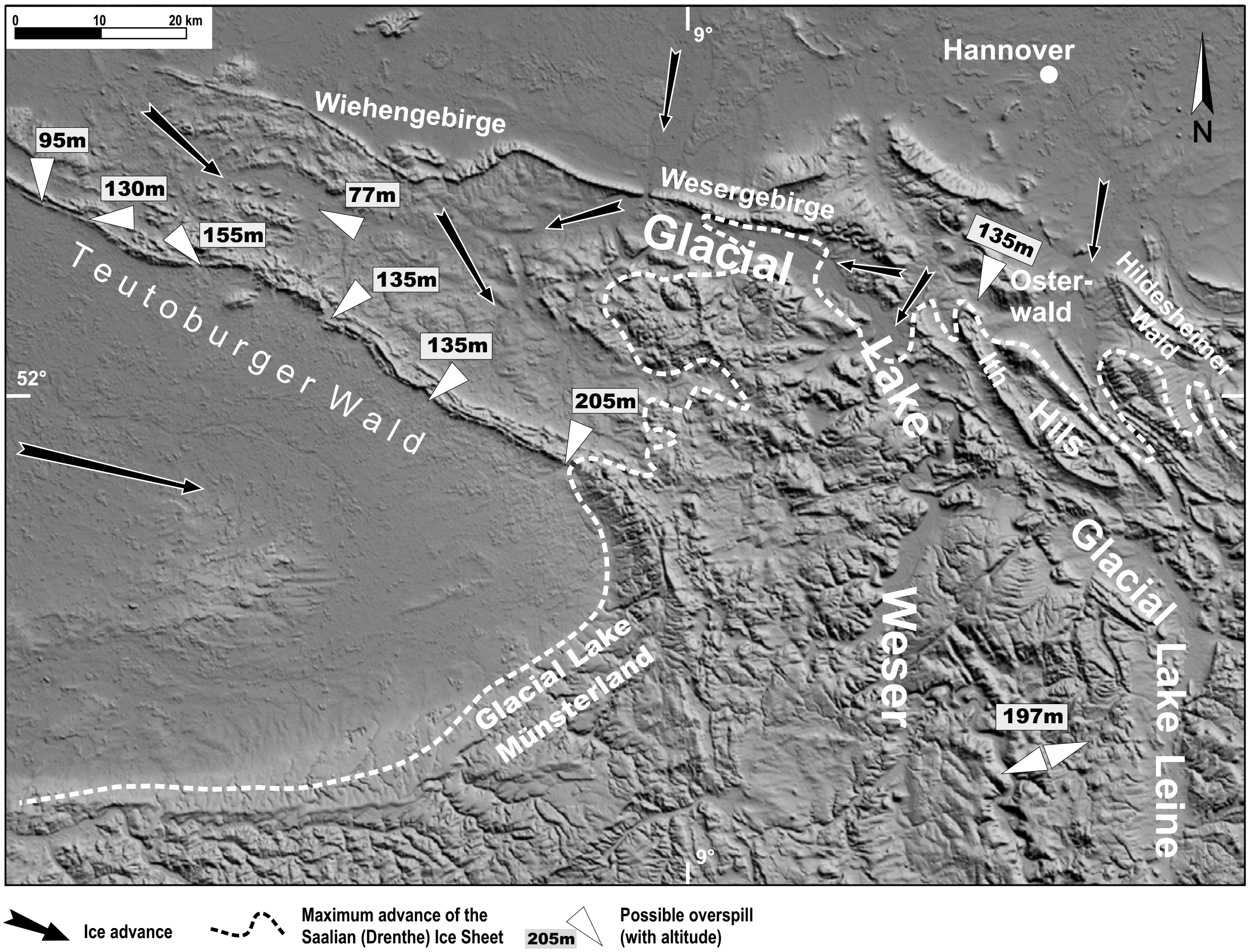

Fig. 2: The shaded relief map of the study area shows the maximum extent of the Saalian Drenthe ice sheet in the study area and major lake overspills. The digital elevation model is based on SRTM data. Modified after Winsemann *et al. (2009).*

Abb. 2: Digitales Höhenmodell des Untersuchungsgebietes mit der Position des maximalen Eisrandes und der Lage der wichtigen See-Überläufe. Das digitale Höhenmodell basiert auf SRTM Daten. Verändert nach Winsemann *et al. (2009).*

Re-examination of ice-marginal depositional systems, including a detailed analysis of the sedimentary facies, depositional processes, stratigraphic architecture and internal deformation patterns by Winsemann et al. (2003), Winsemann, Asprion & Meyer (2004, 2007), Hornung, Asprion & Winsemann (2007), Winsemann et al. (2007, 2009), Brandes, Polom & Winsemann (2011), Winsemann, Brandes & Polom (2011) and Brandes et al. (2011) reveals that these depositional systems represent subaqueous fans and deltas deposited into glacial Lake Weser and glacial Lake Leine. Therefore, the principle lithologic evidence for large and deep glacial lakes in the Upper Weser Valley and Leine Valley is the occurrence of these subaqueous ice-marginal deposits, which can be partly used as water-plane indicators. Boreholes logs and several clay pits record the widespread occurrence of more than 20 m of thick fine-grained lake bottom sediments, overlying Middle Pleistocene fluvial deposits or bedrock.

The longevity of glacial Lake Weser and glacial Lake Leine can only be roughly estimated because varve deposits of the basin centre are only poorly exposed and no undisturbed core data are available. According to Litt et al. (2007) and Busschers et al. (2008), the Saalian Drenthe ice advance probably occurred during MIS 6 and lasted ~5000 years (Lambeck et al. 2006). The longevity of the glacial lakes was probably very short, which has been estimated a few hundred to thousand years (Junge 1998, Winsemann et al. 2009).

3 Data Base and Methods

A total of 27 sand and gravel pits and 4440 borehole logs were evaluated in order to document the regional pattern and character of Saalian glaciolacustrine deposits of the Upper Weser and Leine Valley (Fig. 2 and Fig. 3). Outcrop data are mainly available for the coarse-grained ice-marginal deposits, where sand and gravel has been excavated in numerous open pits. These outcrops were characterized from lateral and vertical measured sections across two- and three-dimensional exposures. The sections were measured at the scale of individual beds, noting grain size, bed thickness, bed contacts, bed geometry, internal sedimentary structures, and palaeocurrent directions. The spatial distribution of specific lithofacies was determined through detailed mapping of hand-drilled borings. The field study was supplemented with a georadar and shear-wave seismic

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survey. In addition, high-resolution digital elevation models were used to analyse geomorphological features of ice-marginal deposits.

The maximum extent and derivative lake-level curve of glacial Lake Weser has been mainly defined by foreset-topset transitions of deltas and a sequence stratigraphic analysis of glaciolacustrine depositional systems (Winsemann, Asprion & Meyer 2007, Winsemann et al. 2009, Winsemann, Brandes & Polom 2011). Although the mapping of shoreline features is an important tool for reconstructing the palaeogeography and lake-level history of Late Pleistocene glacial lakes (e.g., Teller 1995, Carling et al. 2002, Johnsen & Brennand 2006), this method does not work well with older Pleistocene lakes located in high relief areas, where shoreline features are likely to be destroyed or obscured by later periglacial processes and anthropogenic modification (e.g., LaRoque, Dubois & Leblon 2003).

The DEM was combined with information from geological maps (1: 25 000, 1: 100 000), outcrops and borehole logs to document the regional pattern and character of glaciolacustrine deposits in the Upper Weser and Leine Valley. Geographic Information Systems (GIS) were then used for the palaeogeographic reconstruction of glacial Lake Weser and glacial Lake Leine, superimposing water planes onto the land surface DEM.

4 Palaeogeographic reconstruction of glacial Lakes in the Weser- and Leinebergland

4.1 Glacial Lake Weser

During the maximum extent of the Drenthe ice sheet, glacial Lake Weser was dammed in the Upper Weser Valley along with major tributaries. The main spillway system of glacial Lake Weser is a series of valleys in the Teutoburger Wald Mountains over an altitude range of 40–205 m a.s.l. through which the proglacial lake drained south-westward (Thome 1983, 1998, Klostermann 1992, Winsemann et al. 2009 and Winsemann, Brandes & Polom 2011). These overspill channels increase in altitude towards the east (Fig. 2) and were successively closed during ice advance (Thome 1983, Skupin, Speetzen & Zandstra 1993). On the eastern lake margin, two overspill channels are recognized. One is located in the gap between the Osterwald and Ith Mountains (Fig. 2). This potential overspill channel has an altitude of approximately 135 m and was probably closed early during ice lobe advance into the Weser and Leine Valley. Another overspill channel is located farther south at an altitude of ~197 m a.s.l. This overspill channel is located east of Bodenfelde (Fig. 2 and Fig. 3) and is characterized by a 200–500 m wide, flat-floored valley that trends roughly east-west and cuts into Mesozoic bedrocks (e.g., Thome 1998, Winsemann et al., 2007). The valley is now occupied by two underfed rivers. The Schwülme River flows to the west into the Weser River and the Harste River flows to the east into the River Leine.

The principle lithologic evidence for a large and deep glacial lake in the Upper Weser Valley is the occurrence of subaqueous ice-marginal deposits, fine-grained lake bottom sediments, and ice-rafted debris far beyond the former ice margin. The stratigraphic evidence comes from both surface exposures and subsurface data. A total of 20 sand and gravel pits and 2300 borehole logs were evaluated in order to document the regional pattern and character of Middle Pleistocene deposits of the Upper Weser Valley. Outcrop data are mainly available for the coarse-grained ice-marginal deposits, where sand and gravel has been excavated in numerous open pits (Winsemann et al. 2003, Winsemann, Asprion & Meyer 2004, 2007, Hornung, Asprion & Winsemann 2007, Winsemann et al. 2007, 2009 and Winsemann, Brandes & Polom 2011). The subsurface data come from borings drilled along the river valleys and tributaries. Borehole logs and several clay pits record the widespread occurrence of up to 20 m thick fine-grained lake bottom sediments ("Hauptbeckenton"), overlying Middle Pleistocene fluvial deposits of the Weser River („Mittelterrasse") or bedrock (e.g., Winsemann et al. 2009). Former clay pits in the northern lake basin revealed that these lake-bottom sediments are commonly laminated and frequently contain dropstones (e.g., Rausch 1975, Kulle 1985, Wellmann 1998). These fine-grained lake-bottom sediments occur over an altitude range of 55 to 180 m a.s.l. Towards the south, the thickness of lake bottom sediments decreases (< 8 m) and relics of lake-bottom sediments are mainly preserved along the valley sides (Winsemann et al. 2009).

Erratic clasts with a Scandinavian provenance occur within the entire study area (Fig. 3) and have been reported from altitudes of 114–200 m a.s.l. (e.g., Kaltwang 1992, Farrenschon 1995, Rohde & Thiem 1998). These clasts frequently occur beyond the Drenthe ice-margin and therefore have been partly interpreted as relics of the Elsterian glaciation (e.g., Thiem 1988, Rohde & Thiem 1998). New interpretations assume that these clasts represent ice-rafted debris dumped by icebergs. Clasts are commonly associated with fine-grained lake-bottom sediments or overly fluvial deposits. The occurrence in clusters at altitudes of ~130 m and ~185 m may indicate stranded icebergs at former lake shores (Winsemann et al. 2009). Associated beaches or shoreline features like wave-cut benches have not been recognized. It is not clear if beaches could have formed at the steep shores or if they have been destroyed or obscured by later periglacial processes and anthropogenic modification. It is also not known if glacial rebound affected the study area and played a major role in determining the position of former shorelines relative to today's surfaces of lake marginal depositional systems.

The maximum extent and derivative lake-level curve of glacial Lake Weser has been defined by foreset-topset transitions of deltas and a sequence stratigraphic analysis of glaciolacustrine depositional systems (Winsemann, Brandes & Polom 2011). Disruption of drainage by ice advance created glacial Lake Weser at an altitude of ~ 55 m a.s.l. The lake level then rose to a highstand ~200 m a.s.l. caused by the successive closure of lake overspill channels (Fig. 4). Ice-marginal deposits of the north western lake margin (e.g., Markendorf delta and the ice-marginal deposits of the "Ravensberger Kiessandzug", cf. Skupin, Speetzen & Zandstra 2003) became deformed and overridden by the advancing ice sheet. During the maximum lake-level highstand of ~200 m a.s.l., glacial Lake Weser was up to 150 m deep, covered an area of ~1870 km^2 and approximately 120 km^3 of water was stored in the lake basin. The higher topographic position of ice-marginal deposits at the southwestern slope of the Thüster Berg Mountain southeast of Coppenbrügge (Herrmann 1958) can be explained by a higher local lake-level of ~215 a.s.l. within the Hils syncline, which was completely dammed by ice and isolated from glacial Lake Weser and glacial Lake Leine during maximum ice sheet coverage.

The overall lake-level rise of glacial Lake Weser was followed by two high-amplitude lake-level falls (Winsemann, Brandes & Polom 2011). Opening of the 135 m and 95 m lake outlets in the Teutoburger Wald Mountains (Fig. 2) during ice-lobe retreat caused independent catastrophic lake-level drops in the range of 35–65 m (Fig. 4). The lake water drained into the Münsterland Embayment with a peak discharge of probably up to 1 300 000 m^3/s. During these outburst events, deep plunge pools, streamlined hills and trench-like channels were cut into Mesozoic bedrock and Pleistocene deposits (Meinsen et al. in press). Subsequently, a lake-level rise in the range of 30 m occurred, caused by a new ice-lobe advance into the Münsterland Embayment ("Hondsrug ice stream" cf. van den Berg & Beets 1987, Skupin, Speetzen & Zandstra 1993), leading to the renewed closure of the 95 m overspill channel in the Teutoburger Wald Mountains and the observed lake-level rise (Fig. 4). Rapid destabilization of this ice-lobe led to the final drainage of the Weser Lake.

4.2 Glacial Lake Leine

During the maximum extent of the Drenthe ice sheet, an ice-dammed lake developed within the Upper Leine and Rhume Valley, referred to as "glacial Lake Leine" (Thome 1998, Winsemann et al. 2007). The main spillway system of glacial Lake Leine is the overspill channel in the gap between the Osterwald and Ith Mountains at an altitude of approximately 135 m a.s.l. and the broad, east-west trending valley east of Bodenfelde at ~197 m a.s.l. Thick accumulation of fine-grained lake-bottom sediments at the eastern valley outlet (Jordan 1984) may indicate a preferred overflow from glacial Lake Weser into glacial Lake Leine (Fig. 3), although the contour lines of the overspill channel may also point to a temporal westward-directed overflow from glacial Lake Leine into glacial Lake Weser. A third overspill channel is located on the northeastern margin of glacial Lake Leine, connecting the Leine Lake with the Nette Valley (Fig. 3). This overspill channel also has an altitude of ~200 m and more than 20 m thick accumulation of fine-grained lake-bottom sediments in front of the western channel outlet (e.g., Jordan 1993) points to mainly south westward-directed overflows from the Nette Lake into the Leine Lake.

As in the Weser Valley, the principle lithologic evidence for a large and deep glacial lake in the Upper Leine Valley is the occurrence of subaqueous ice-marginal deposits and fine-grained lake bottom sediments. Some isolated erratic clasts with a Scandinavian/Baltic provenance have been described from the area near Ahlshausen south east of Bad Gandersheim and been interpreted to represent relics of an Elsterian glaciation (Jordan & Schwartau 1993). However, these clasts may also represent ice-rafted debris dumped by icebergs. A total of 7 sand and gravel pits and 2140 borehole logs were evaluated in order to document the regional pattern and character of Middle Pleistocene deposits in the Upper Leine Valley. Borehole logs record the widespread occurrence of up to 20 m thick fine-grained lake bottom sediments within the entire study area over an altitude range of 80–190 m a.s.l. (Fig. 3). The maximum thickness of lake-bottom deposits is recorded west of Northeim and Nörten-Hardenberg, where up to 50 m of fine-grained sediments have been drilled (e.g., Jordan 1984, 1986). This area belongs to a complex pull-apart basin system that evolved during the late Cretaceous (Vollbrecht & Tanner in press) and provided the accommodation space.

The age of the fine-grained lake sediments of the Upper Leine Valley is poorly constrained. They are commonly overlain by late Pleistocene fluvial or aeolian deposits and partly overlie Upper Pleistocene fluvial deposits ("Mittelterrasse), pointing to a Saalian age. However, the sediments have not been absolutely dated and it is possible that thick successions of fine-grained lake bottom sediments may also comprise older Middle and Lower Pleistocene deposits (e.g., Jordan 1984, 1986, 1993).

The lake-level history of glacial Lake Leine has not been reconstructed in detail. Recently a new field study supplemented with a shear-wave seismic survey was carried out to reconstruct the palaeogeographic evolution and lake-level history of glacial Lake Leine (Wahle et al. 2010). The palaeogeographic reconstruction of the Leine Lake shown in Figure 3 is based on well data and mapped glaciolacustrine ice-marginal deposits. During highstand, glacial Lake Leine probably reached a lake-level of ~200 m a.s.l. as is indicated by the topographic position of glaciolacustrine ice-marginal deposits and fine-grained lake bottom sediments, corresponding with a lake area of ~900 km^2, a water volume of up to ~36 km^3 and a water depth of up to ~90 m. During deglaciation the ice probably rapidly retreated northwards, indicated by northward-stepping small bead-like sediment bodies (Lüttig 1960, Jordan 1989). A new ice margin stabilized in front of the Osterwald and Hildesheimer Wald Mountains, which acted as a pinning point.

5 Depositional Archtitecture of Glaciolacustrine ice-marginal deposits

5.1 Glacial Lake Weser

Three major subaqueous fan and delta complexes are recognized on the northern margin of glacial Lake Weser, which can be related to the ice-front position of the Drenthe ice sheet. From east to west, these are the Porta subaqueous fan and delta complex, the Emme delta, and the Coppenbrügge subaqueous fan complex (Fig. 3).

5.1.1 The Porta subaqueous fan and delta complex

The Porta ice-margin deposits are located south of the Porta Westfalica pass, which has an altitude of 42 m. Deposits were well-exposed in numerous sand and gravel pits (Fig. 5) and have previously been described by several authors. Most previous workers assumed a subaerial morainal, glaciofluvial, kame or fluvial origin for the Porta ice-margin deposits (e.g., Koken 1901, Struck 1904, Spethmann 1908, Siegert 1912, Driever 1921, Naumann 1922, Grupe 1930, Stach 1930, Grupe et al. 1933, Miotke

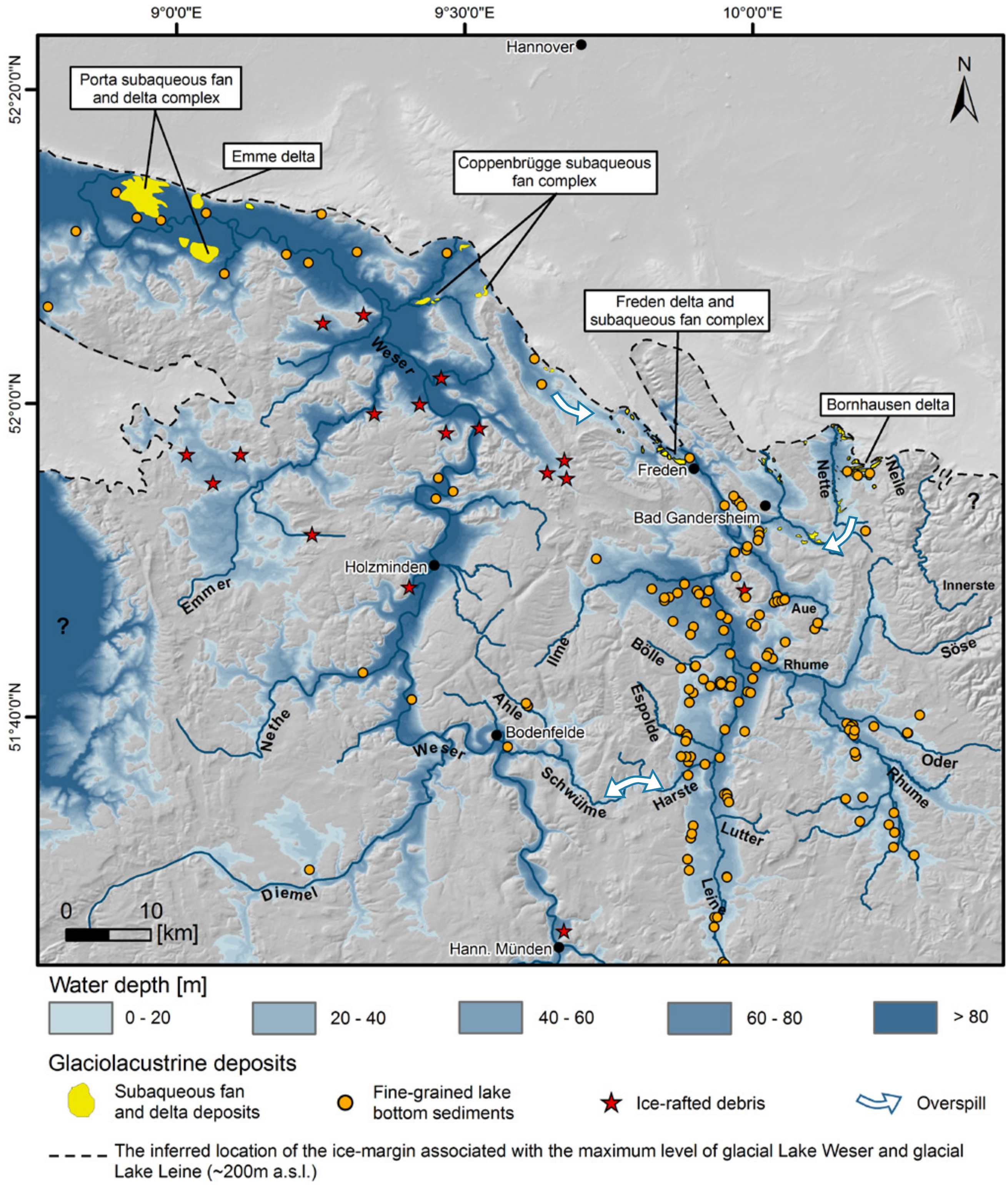

Fig. 3: Detail map of the study area, showing a palaeogeographic reconstruction of glacial Lake Weser and glacial Lake Leine and associated ice-marginal depositional systems, ice-rafted debris and lake-bottom sediments. Data are compiled from map sheets 1: 25 000, outcrop data and wells.

Abb. 3: Detail-Karte des Untersuchungsgebietes mit der paläogeographischen Rekonstruktion des Weser- und Leine-Eisstausees. Dargestellt sind die assoziierten Eisrand- Ablagerungssysteme, erratische Blöcke und feinkörnige Becken-Ablagerungen. Die Daten wurden aus geologischen Karten (1: 25 000), Aufschlüssen und Bohrungen kompiliert.

1971, Seraphim 1973, Deutloff et al. 1982, Röhm 1985, Groetzner 1995, Könemann 1995, Wellmann 1998, Elbracht 2002).

Re-examination of outcrops by Hornung, Asprion & Winsemann (2007), Winsemann, Asprion & Meyer (2007) and Winsemann et al. (2009) reveal a subaqueous origin for the Porta ice-margin deposits. Several sedimentary characteristics indicative of subaqueous deposition were recorded. Data critical to this re-interpretation include the recognition of jet-efflux deposits, turbidites, ice-rafted debris dumped by icebergs, and Gilbert-type delta deposits. These coarse-grained ice-marginal deposits overlie 0.3–20 m

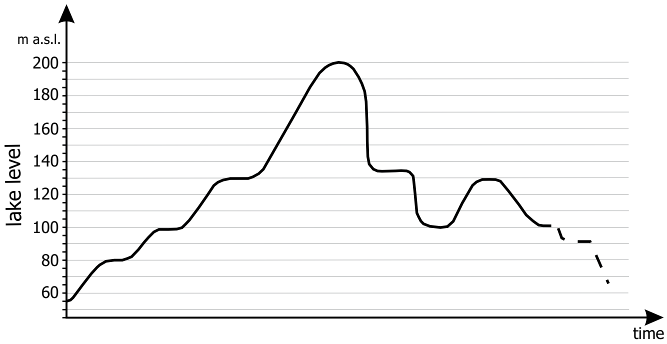

Fig. 4: Reconstructed lake-level curve of glacial Lake Weser. Modified after Winsemann, Brandes & Polom (2011). The longevity of glacial Lake Weser can only be roughly estimated and has probably been a few hundred to thousand years.

Abb. 4: Rekonstruktion der Seespiegelkurve des Weser-Eisstausees (verändert nach Winsemann, Brandes & Polom 2011). Die Lebensdauer des Sees kann nur grob abgeschätzt werden und betrug vermutlich nur wenige 100 bis 1000 Jahre.

thick glaciolacustrine mud and patchy occurrences of till (Könemann 1995, Wellmann 1998, Winsemann et al. 2009). Clasts consist mainly of local material derived from the adjacent Mesozoic basement rocks and reworked fluvial gravel, previously deposited by the Weser River. Clasts with a Scandinavian and/or Baltic provenance account for 2–12 % (Röhm 1985, Wellmann 1998). Southward palaeoflow directions and clast composition indicate that meltwater flows were the main source of sediment (Winsemann et al. 2009).

Three fan complexes can be recognized (Fig. 5), deposited on a flat lake-bottom surface and characterized by vertically and laterally stacked, moderately- to steeply-dipping sediment bodies. The northernmost fan body is unconformably overlain by two generations of Gilbert-type deltas (Winsemann et al. 2009). The extent, morphology, clast composition and sedimentary facies indicate deposition into a lake at the margin of the retreating Porta ice lobe. The ice lobe retreat was probably caused by the overall lake-level rise (Fig. 4) that led to a destabilisation of the ice margin. The ice-margin eventually became re-stabilized near the Porta Westfalica pass, where a stable meltwater tunnel facilitated the construction of a large subaqueous fan and delta complex.

Fan complex I

The stratigraphically lowest fan (fan complex I, Fig. 5) is up to 60 m thick and consists of moderately to steeply dipping mid-fan deposits, characterized by graded-stratified sand and channelized large-scale trough cross-stratified sand and gravel. These mid-fan deposits unconformably overlie flat-lying planar cross-stratified proximal fan gravel (Winsemann, Asprion & Meyer 2007a). The sedimentary sequence is partly deformed, displaying thrusts, dipping towards the northwest and overlain by flow till and glaciolacustrine mud (Wellmann 1998). Towards the south the fan deposits interfinger with dropstone laminites (Rausch 1975).

Fan complex II

Fan complex II (Fig. 5) consists of 9 m thick massive, normally graded or large-scale trough-cross stratified proximal fan gravel, unconformably overlain by 15 m thick moderately- to steeply-dipping distal mid-fan deposits, characterized by medium- to thick-bedded inversely graded, massive, diffusely stratified pebbly sand or normally graded sand to mud beds. This succession shows an overall fining- and thinning upward trend.

Fan complex III

Fan complex III is exposed in several gravel pits south of the Porta Westfalica pass (Fig. 5). To determine the larger-scale architecture of the northern Porta complex, shear wave seismic reflection profiles have been acquired and analyzed (Fig. 6 and Fig. 7). The greatest thickness of fan deposits is recorded from a central, ~1 km wide and 5.4 km long, NW-SE trending zone (Fig. 6 and Fig. 7). Deposits, exposed in this central zone consist of highly scoured massive, normally graded, planar-parallel or cross-stratified gravel, interpreted to have been deposited from a friction-dominated plane-wall jet at the mouth of a subglacial meltwater tunnel (Hornung, Asprion & Winsemann 2007, Winsemann et al. 2009). Subsequent flow-splitting led to the development of smaller jets at the periphery of this bar-like deposits and the deposition of more sand-rich jet-efflux deposits characterized by large-scale trough-cross stratified gravel, pebbly sand and sand (Fig. 7B and C).

During the subsequent high-magnitude lake-level drops (Fig. 4), the subaqueous fan became truncated and overlain by delta deposits. Two different Gilbert-type deltas can be recognized, which were formerly exposed in the Müller 2 and Hainholz pit (Fig. 5, Fig. 6 and Fig. 7B). These deltas are separated by a major erosional unconformity. The first delta generation is characterized by steep and coarse-grained delta foreset beds, deposited from cohesionless debris flows and high- to low-density turbidity currents, indicating a steep high-energy setting (Fig. 7B and D). These delta deposits resembles those exposed in the Emme delta and are unconformably overlain by finer-grained delta sediments, deposited mainly from tractional flows and representing a shallower, lower-energy setting and the formation of a larger delta plain (Fig. 7E) during the subsequent lake-level rise (Fig. 4).

Internal deformation pattern

The deformation of the Porta deposits includes both contractional and extensional structures. The observed north-westward dipping thrusts within Fan complex I (Wellmann 1998) record glaciotectonic deformation of previously deposited ice-margin sediments, probably related to seasonal ice-margin fluctuations. A simple graben system is developed in the Mesozoic basement rocks below the central fan area (Fig. 7B). Single normal faults propagate into the overlying Pleistocene deposits, indicating a Pleistocene reactivation of Upper Triassic to Lower Jurassic deformation structures. Within the coarse-grained central fan deposits, a series of steep normal faults are recorded, which are restricted to the fan body. These are not related to the basement tectonics and therefore are interpreted as compactional or gravitational deformation features. Larger-scale delta channel-fills, previously exposed in the Müller 2 pit (Fig. 5) show high-angle (65–90°) gravitational synsedimentary normal faults (vertical offset 0.1–1.2 m), which are parallel to the channel-margins. This

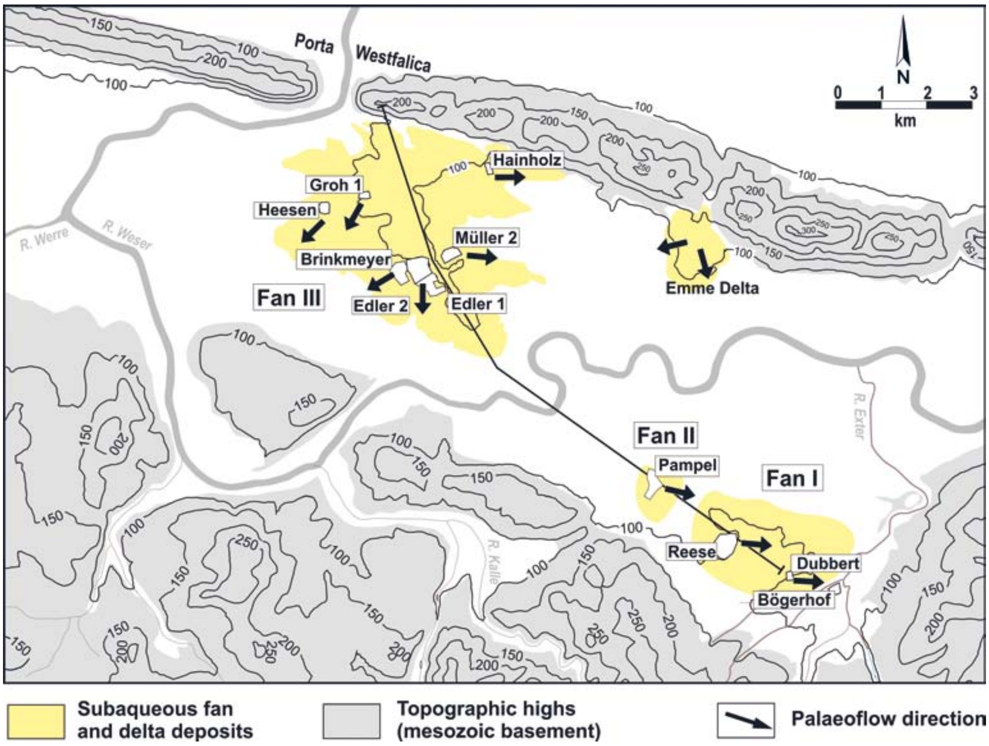

Fig. 5: Location of the Porta complex and the Emme delta. Modified after Winsemann *et al. (2009).*

Abb. 5: Lage des Porta Komplexes und des Emme Deltas. Verändert nach Winsemann *et al. (2009).*

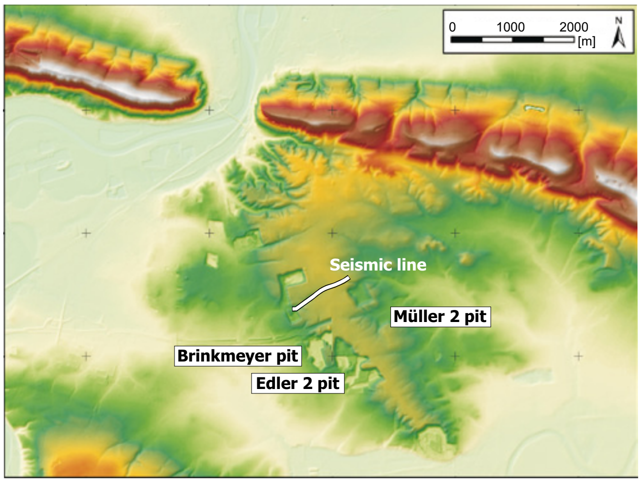

Fig. 6: Hill-shaded relief model of the northern Porta complex (fan complex III), showing the location of the shear-wave seismic profile. The digital elevation model is based on data from the Landesvermessungsamt Nordrhein-Westfalen.

Abb. 6: Digitales Höhenmodell des nördlichen Porta Komplexes (fan complex III) mit der Lage des Scherwellen-Seismik Profils. Das digitale Höhenmodell basiert auf Daten des Landesvermessungsamts Nordrhein-Westfalen.

kind of gravitational deformation is known from many marine deep-water channel-levee systems (e.g., Clark & Pickering 1996, Moretti et al. 2003).

5.1.2 The Emme delta

The Emme deposits are located south of the Kleinenbremen pass, which has an altitude of ~153 m. The radial sediment body is about 2 km long, 1.8 km wide and up to 70 m thick, overlying a concave, up to 13° steep dipping ramp surface. The sediment body has a stepped profile with two plains at ~128 m and ~155 m a.s.l. The upper portion is characterized by a central, trumpet-shaped, up to 20 m deep valley that rapidly shallows downslope (Fig. 8).

The deposits were well-exposed in several sand and gravel pits over an altitude range of 95–165 m and have previously been described by several authors who assumed a subaerial kame or alluvial fan formation (Grupe 1930, Stach 1930, Attig 1965, Miotke 1971, Hesemann 1975, Merkt 1978, Rakowski 1990 & Groetzner 1995). Clasts mainly consist of poorly sorted, angular local material derived from steep Mesozoic bedrock slopes. Clasts with a Scandinavian / Baltic provenance account for approximately 10% (Rakowski 1990). More recently the Emme deposits were interpreted as a delta (Thome 1998, Jarek 1999, Winsemann, Asprion & Meyer 2004, Winsemann, Brandes & Polom 2011).

The data derived from outcrop analysis suggests Gilbert-type delta sedimentation (Winsemann, Asprion & Meyer 2004, Winsemann, Brandes & Polom 2011). High-angle bedding and coarse-grained foreset deposits indicate steep slopes with gravity driven flows. Material that bypassed the braid plain avalanched downslope as cohesionless debris flows and was deposited en-masse when the slope diminished. The finer-grained sandy material moved farther downflow where it was deposited from diluted debris flows and turbidity flows. Topset deposits in outcrop sections have mostly been eroded and are only locally preserved as channel-fills, overlying truncated delta foresets (Winsemann, Brandes & Polom 2011).

To determine the larger-scale architecture of the Emme delta complex, 3 shear wave seismic reflection profiles have been acquired and analyzed. The seismic sections show a complex pattern of 9 vertically and laterally stacked depositional units (Fig. 9). The oldest depositional units are vertically stacked, decreasing upwards in thickness and lateral extent. These depositional units are incised by an up to 150 m wide and 20 m deep incised valley and fringed

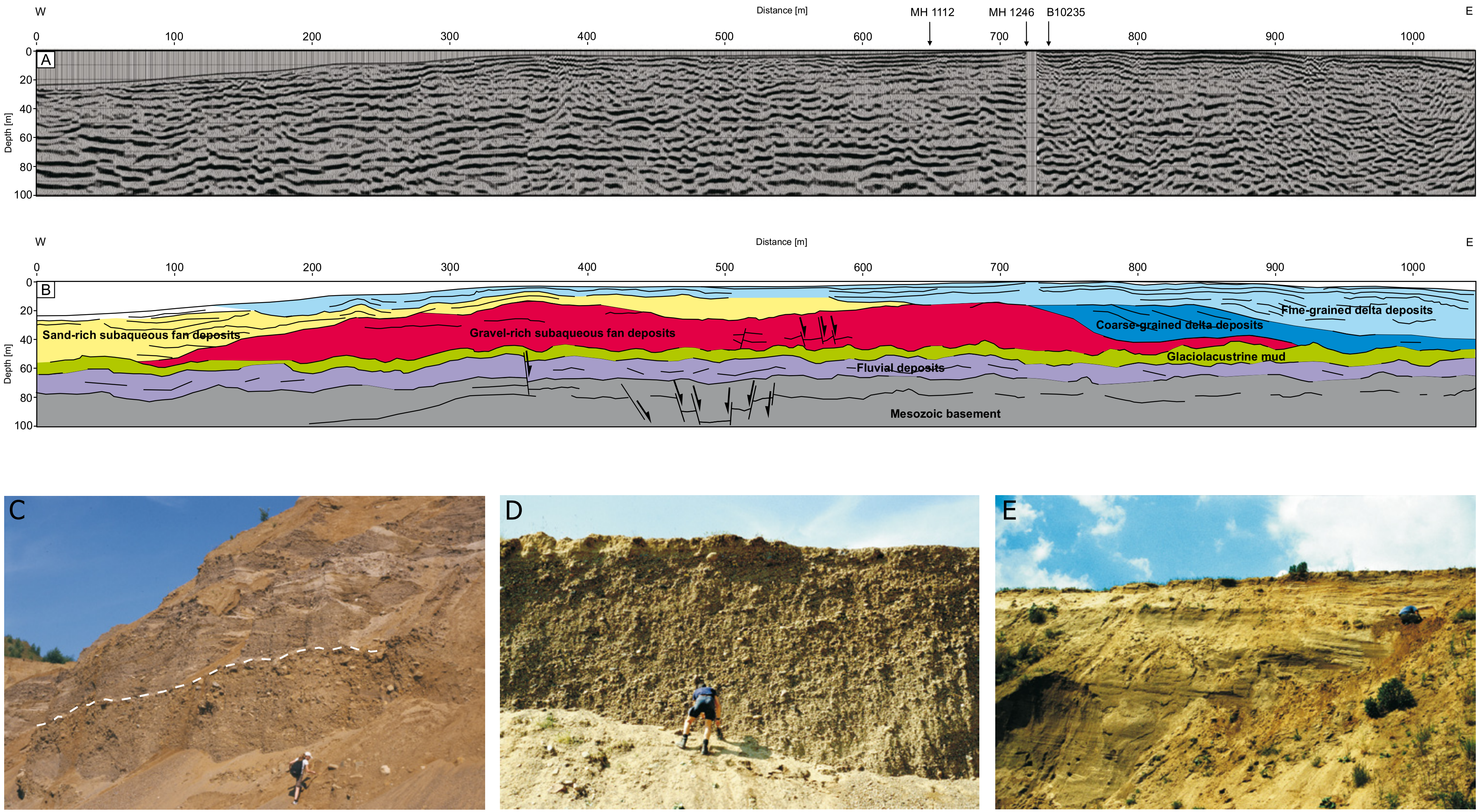

Fig. 7: Depositional architecture and sedimentary facies of the Porta complex. A and B) Shear-wave seismic profile measured north of the gravel pits Brinkmeyer, Edler 2 and Müller 2 (for location see Fig. 6). Coarse-grained subaqueous fan deposits overlie fluvial deposits of the Weser River and lake-bottom sediments. The subaqueous fan deposits are unconformably overlain by two generations of delta deposits. C) Photograph of scoured massive gravel, erosively overlain by scoured planar and trough cross-stratified gravel and pebbly sand (proximal jet-efflux deposits of the incipient subaqueous fan, Brinkmeyer pit). Palaeoflow directions are towards the south and south west. D) Steeply (8–35°) eastward-dipping coarse-grained delta foreset deposits of the older delta system (Hainholz pit). E) Gently (5–15°) eastward-dipping fine-grained delta deposits, unconformably overlying the older coarse-grained Gilbert-type delta (Hainholz pit).

Abb. 7: Architektur und Sedimentfazies des Porta Komplexes. A und B) Scherwellen-Seismik Profil, das nördlich der Gruben Brinkmeyer, Edler 2 und Müller 2 gemessen wurde (Abb. 5 und Abb. 6). Grobkörnige subaquatische Fächer-Ablagerungen überlagern fluviatile Sedimente der Weser und feinkörnige Becken-Ablagerungen. Die subaquatischen Fächer-Ablagerungen werden diskordant von zwei unterschiedlichen Delta-Systemen überlagert. C) Massive grobkörnige Kiese mit zahlreichen kolkartigen Erosionsstrukturen werden diskordant von schräggeschichteten Kiesen und geröllführenden Sanden überlagert (proximale „jet-efflux“ Ablagerungen des initialen subaquatischen Fächers, Grube Brinkmeyer). Die Paläoströmungsrichtungen verlaufen in südlicher bis südwestlicher Richtung. D) Steil (8–35°) nach Osten einfallende grobkörnige Delta Foreset-Ablagerungen des älteren Delta-Systems (Grube Hainholz). E) Flach (5–15°) nach Osten einfallende feinkörnige Delta-Ablagerungen, die die älteren grobkörnigen Delta-Ablagerungen diskordant überlagen (Grube Hainholz).

by younger, basin ward-stepping units. The youngest features are long-wavelength (60–80 m) bedforms on the south eastern portion of the delta, which erosively overlie the delta lobe deposits and pass downslope into subhorizontal and inclined continuous, high-amplitude reflectors (unit 9). This complex stacking pattern is attributed to delta lobe switching during progradation and base-level change (Winsemann, Brandes & Polom 2011). During the overall lake-level rise, vertically stacked delta systems formed. The decrease in thickness and lateral extent indicates a rapid upslope shift of depocenters. The facies distribution during rapid, high-magnitude lake-level fall (~65 m) was controlled by the formation of a single incised valley, which captured the sediment and focussed the sediment supply to regressive lobes in front of the incised fairway, as shown in numerical simulations by Ritchie, Gawthorpe & Hardy (2004 a). The incised valley was filled due to delta plain/glaciofluvial aggradation during decreasing rates of lake-level fall and lake-level lowstand. This matches results from flume tank experiments, carried out by Petter & Muto (2008) for systems where the alluvial gradient exceeds the shelf gradient, as conceptualized by various authors (e.g., Posamentier, Allan & James 1992, Schumm 1993, Blum & Törnqvist 2000). Attached sand-rich forced regressive aprons formed during lower magnitudes of lake-level fall in the range of 35 m. The formation of attached aprons has been attributed to low rates of lake-level fall or a rapid fall associated with high sedimentation rates, causing only minor incision (e.g., Ritchie, Gawthorpe & Hardy 2004 a, b). In the case of the Emme delta, rates of lake-level fall were high due to the opening of lake outlets. Deep valley incision occurred, but was limited to the uppermost portion of the delta, controlled by the steep slope. The incised valley was probably filled during lake-level lowstand and lake-level rise. However, the valley was never flooded during transgression and the shoreline remained basinward of the incised valley. The incised valley related to the final lake drainage is associated with long-wavelength (60–90 m) bedforms at the downslope end, attributed to the formation of antidunes and standing waves as a result of a hydraulic jump. The calculated palaeoflow depth during standing wave formation was 9–14 m and flow velocity was 10–12 m/s (Winsemann, Brandes & Polom 2011).

The stepped geomorphological profile of the Emme delta is the result of vertically and laterally shifting delta lobes during lake-level fluctuations. However, it seems to be very difficult to define discrete lake-levels from geomorphology alone (e.g., Thome 1998), because it is not possible to reconstruct the complex depositional history.

Internal deformation pattern

In the Emme delta, two different fault systems developed, both showing synsedimentary activity (Fig. 9). The faults have planar to slightly listric geometries and show vertical offsets in the range of 2 to 15 m. They form small graben and half-graben systems, which locally show roll-over struc-

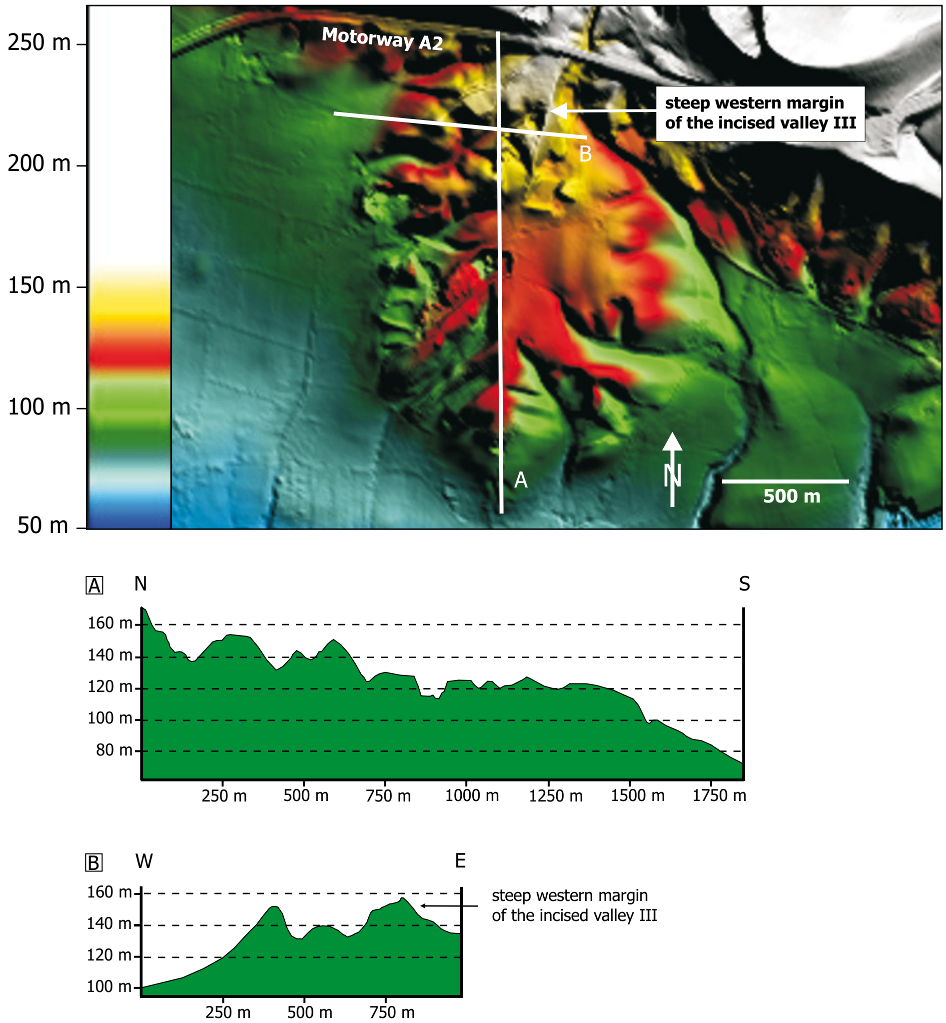

Fig. 8: Hill-shaded relief model of the Emme delta. Cross-sections show the stepped profile of the Emme delta with two plains at ~128 m and ~155 m. Note the steep western margin of the central incised valley. The digital elevation model is based on data from the Landesvermessungsamt Nordrhein-Westfalen. Modified after Winsemann, Brandes & Polom (2011).

Abb. 8: Digitales Höhenmodell des Emme Deltas. Die Schnitte zeigen den steilen westlichen Rand des zentralen Tales („incised valley III") sowie das gestufte Profil des Emme Deltas mit zwei ausgeprägten Niveaus auf einer Höhe von ~128 m und ~155 m ü. NN. Das digitale Höhenmodell basiert auf Daten des Landesvermessungsamts Nordrhein-Westfalen. Verändert nach Winsemann, Brandes & Polom (2011).

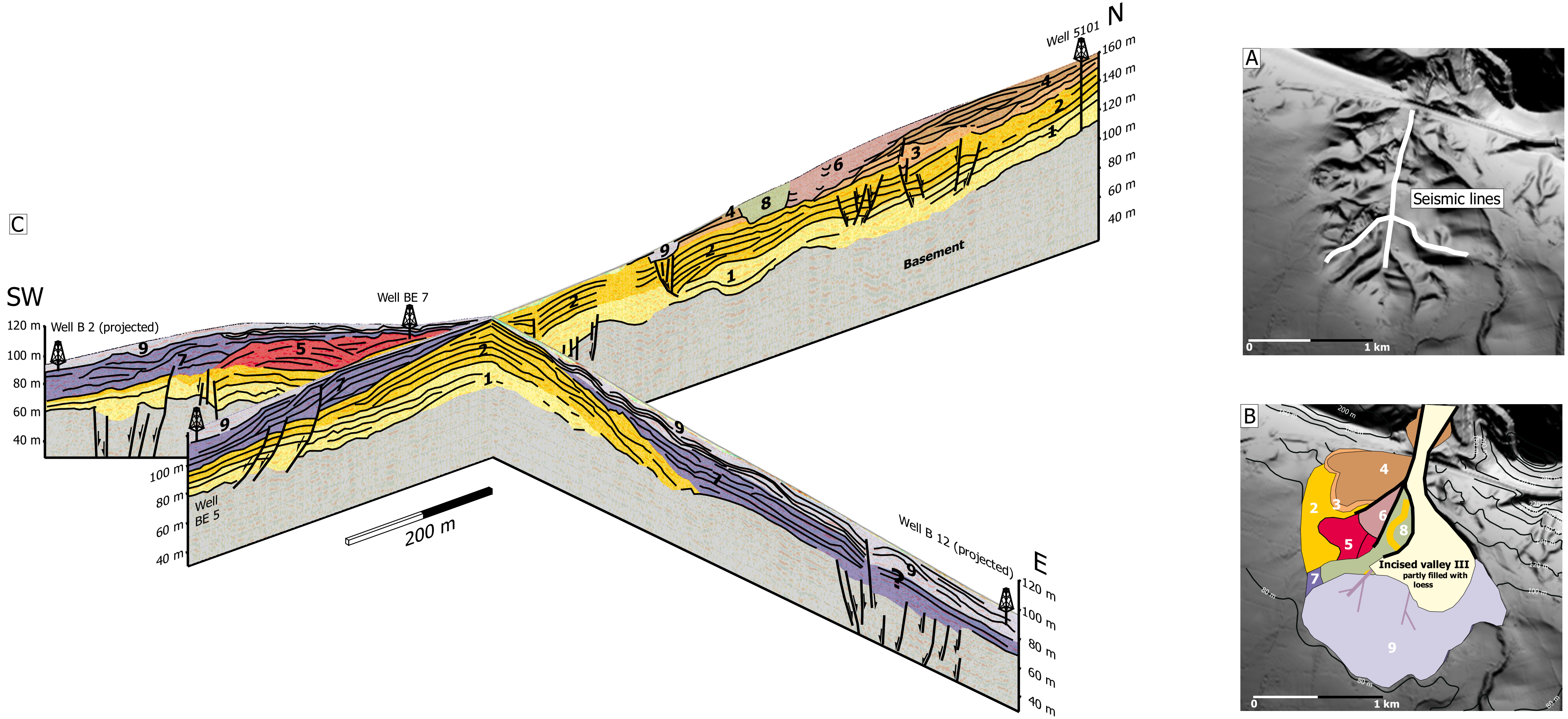

Fig. 9: Depositional architecture of the Emme delta. A) Hill-shaded relief model of the Emme delta with location of measured seismic lines. B) Palaeogeographic reconstruction of the Emme delta, showing major depositional units. C) Fence diagram of seismic lines, showing major seismic units. The early delta development is characterized by back-stepping delta lobes (unit 1–4), deposited during an overall lake-level rise. A catastrophic lake-level fall in the range of ~65 m led to the incision of a deep NE-SW trending valley, in front of which coarse-grained delta lobes were deposited (unit 5). The deposition and upslope shift of finer-grained delta lobes indicates a decrease in flow velocity and sediment supply, probably related to a fluvial/delta plain aggradation in the incised valley (unit 6) during decreasing rates of lake-level fall and subsequent lake-level stillstand. A second valley incision occurred during a lake-level fall of ~35 m. Subsequently a continuous fringe of sandy delta lobes was deposited in the lower portion of the Emme delta (unit 7). Back-filling of the incised valley (unit 8) occurred during lake-level rise (~35 m). During final lake drainage, a new NNW-SEE trending valley formed (incised valley III). Associated are long-wave-length bedforms and the deposition of small-sized sandy lobe and delta-plain deposits (unit 9). The upper deep part of the incised valley is widely unfilled; the lower, shallow part became covered by loess after delta abandonment. Modified after Winsemann, Brandes & Polom (2011).

Abb. 9: Architektur des Emme Deltas. A) Digitales Höhenmodell des Emme Deltas mit der Lage der gemessenen Scherwellen-Seismik Profile. B) Paläogeographische Rekonstruktion des Emme Deltas mit den Haupt-Ablagerungseinheiten. C) Zusammengesetze seismische Profile mit den wichtigen seismischen Einheiten des Emme Deltas. Die frühe Delta-Entwicklung wird durch vertikal gestapelte, rückschreitende Delta-Loben gekennzeichnet (Einheit 1–4), die während eines Seespiegelanstiegs abgelagert wurden. Ein katastrophaler Seespiegelabfall im Bereich von 65 m führte zum Einschneiden eines NE-SW verlaufenden, tiefen Tals. Vor diesem Tal („incised valley I") wurden grobkörnige Delta-Loben abgelagert (Einheit 5). Die nachfolgende Ablagerung von feinerkörnigen Delta-Loben zeigt eine Abnahme der Fließgeschwindigkeit und des Sedimenteintrages an, die vermutlich mit einer zunehmenden Aggradation im Bereich des eingeschnittenen Tals zusammenhängen (Einheit 6). Diese Verlagerung der Sedimentation zeigt eine Abnahme der Fallrate bzw. einen Seespiegel-Stillstand an. Ein zweites Tal („incised valley II") entstand während eines nachfolgenden Seespiegelabfalls im Bereich von 35 m. Nach diesem Seespiegelabfall wurden sandige Delta-Loben im unteren Bereich des Emme Deltas abgelagert, die einen zusammenhängenden Saum bilden (Einheit 7). Die Rückverfüllung des Tals (Einheit 8) erfolgte während eines neuen Seespiegelanstiegs im Bereich von 35 m. Während der finalen See-Drainage bildete sich ein neues, NNW-SEE verlaufendes Tal („incised valley III"). Assoziiert sind lang-wellige Bankformen, kleindimensionierte sandige Loben und Ablagerungen auf der Delta-Ebene (Einheit 9). Der obere Bereich des eingeschnittenen Tals ist weitgehend unverfüllt; der untere Bereich ist mit Löss verfüllt. Verändert nach Winsemann, Brandes & Polom (2011).

tures. The fill of the half-grabens has a wedge-shaped geometry, with the greatest sediment thickness close to the fault (Brandes, Polom & Winsemann 2011). The fault system in the upper portion of the Emme delta is restricted to the delta body and probably gravity induced like in many other deltas (e.g., Bilotti & Shaw 2005). In the lower portion of the delta, however, normal faults occur that originate in the underlying Jurassic basement rocks and penetrate into the delta deposits. The trend of these faults follows extensional structures created by a Late Triassic to Early Jurassic deformation phase. It is very likely that these faults were reactivated during the Pleistocene.

5.1.3 The Coppenbrügge subaqueous fan complex

The Coppenbrügge fan complex is located on the northeastern margin of glacial Lake Weser and consists of 3 small-scale sediment bodies (Fig. 10), deposited on a hummocky low-angle basin slope. The deposits were exposed in various gravel pits over an altitude range of 90–170 m and overlie glaciolacustrine mud and a diamicton, interpreted to represent a basal till (Deters 1999). Clasts consist mainly of resedimented fluvial material (95 %), previously deposited by the Leine River and Weser River or originated from adjacent Mesozoic bedrock (Rausch 1977, Deters 1999). Most previous field studies have assumed a subaerial end moraine, glaciofluvial kames or fluvial origin for the Coppenbrügge deposits (Grupe 1930, Naumann 1927, Naumann & Burre 1927, Lüttig 1954, 1960, Rausch 1977, Deters 1999, Elbracht 2002).

Re-examination of outcrops by Meyer (2003), Winsemann et al. (2003) and Winsemann, Aspion & Meyer (2004, 2007) suggests a subaqueous origin for the Coppenbrügge ice-margin deposits. Several sediment characteristics indicative of subaqueous deposition were recorded. Data critical to this re-interpretation include the recognition of subaqueous jet-efflux deposits, turbidites, thick climbing-ripple cross-laminated units, ice-rafted debris dumped by icebergs and the occurrence of an iceberg scour. The lack of any subaerial glaciofluvial or distributary delta-plain components and the frequent occurrence of ice-rafted debris point to a subaqueous ice-contact fan setting (e.g., Lønne, 1995).

The retrogradational fan bodies accumulated from an easterly and northerly direction as several small subaqueous fans, indicating small conduits with minor effluxes which more easily mix with lake water, so constraining the distance of sediment dispersal (e.g., Fyfe 1990, Powell 1990). Bedrock highs acted as pinning points for the retreating glacier. The stratigraphic record indicates a retreat of active ice, which occurred by calving.

The stratigraphically lowest fan system overlies lake-bottom sediments and was exposed in the Otto pit at an altitude of 84–100 m. The deposits are partly overlain by a basal till and display thrusts, dipping to the east, probably indicating ice-margin fluctuations during overall retreat (Winsemann, Asprion & Meyer 2007).

Fan II overlies a basal till and is exposed at an altitude of 144–155 a.s.l. at the open-pit HBT and Heerburg. Fan III was exposed at an altitude of 143–165 m at the open-pit Heerburg and pit Steinbrink (Fig. 10). On top of fan III, a prominent iceberg scour mark occurred (Fig. 11A and D), overlain by coarsening-upwards mid-fan deposits. The overall coarsening upwards of the uppermost section indicates the progradation of a new fan system (Fan IV) from the east.

Individual fan bodies commonly have a coarse-grained proximal core of steeply dipping upper fan gravel, disconformably overlain by sandy outer- to mid-fan deposits. Climbing-ripple cross-laminated and large-scale cross-stratified sand may onlap coarse-grained upper fan gravel of stratigraphic lower fan bodies and in some cases overtops the older fan deposits (Fig.11). Deposits of the proximal fan

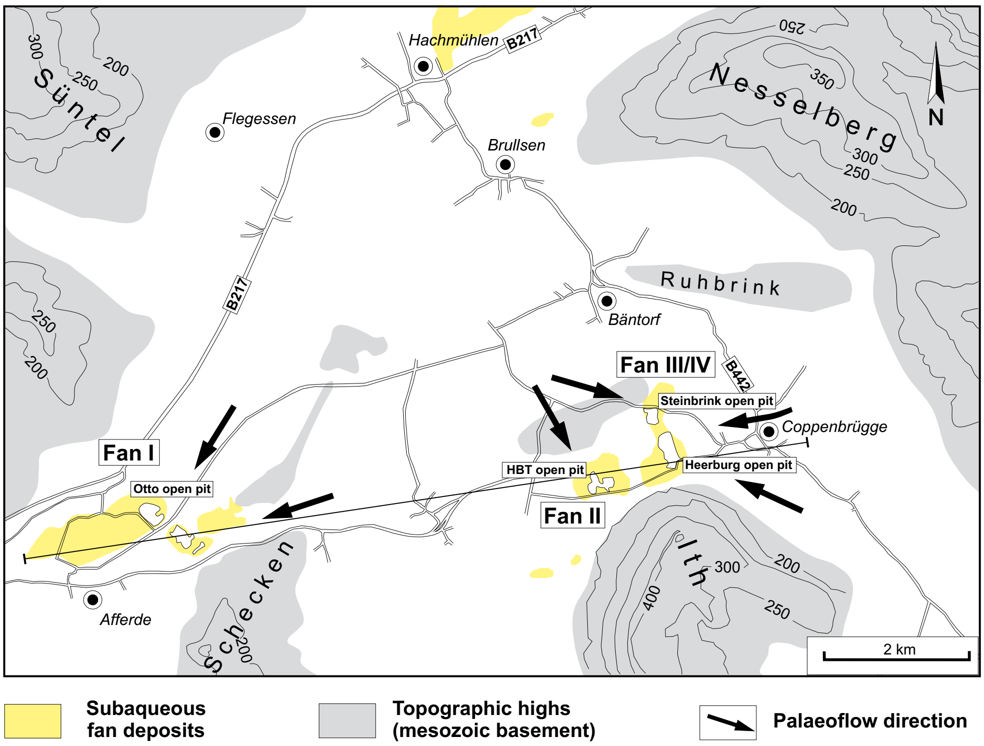

Fig. 10: Location of the Coppenbrügge subaqueous fan. Modified after Winsemann, Asprion & Meyer (2007).

Abb. 10: Lage des subaquatischen Coppenbrügge Fächers. Verändert nach Winsemann, Asprion & Meyer (2007).

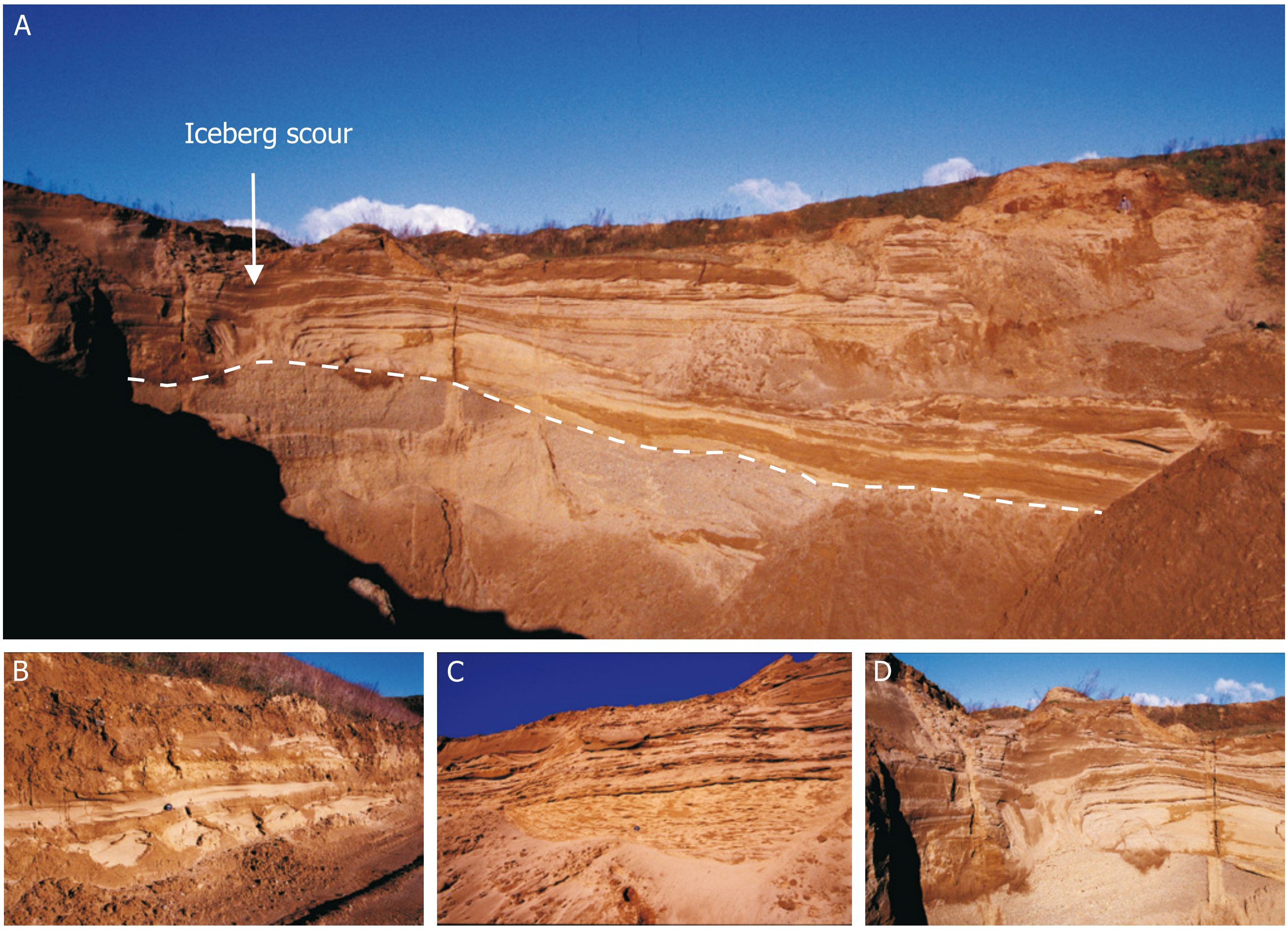

Fig. 11: Depositional architecture and sedimentary facies of the Coppenbrügge subaqueous fan. A) Coarse-grained upper fan deposits, unconformably overlain by finer-grained outer- to mid-fan deposits recording a rapid ice-margin retreat and deposition on the back-slope of the abandoned fan. Note iceberg scour on top of the abandoned fan. B) Close-up view of fine-grained lower-fan deposits with ball and pillow structures, indicating high sedimentation rates. C) Close-up view of climbing-ripple cross-laminated sand; ripples migrate upslope. D) Close-up view of the iceberg scour on top of the abandoned fan. The scour is approximately 1.5 m deep and up to 1.5 m wide.

Abb. 11: Architektur und Sedimentfazies des subaquatischen Coppenbrügge Fächers. A) Grobkörnige Ablagerungen des oberen Fächers, werden diskordant von feinerkörnigen Ablagerungen des äußeren und mittleren Fächers überlagert. Dies zeigt einen schnellen Eisrückzug an, der mit Ablagerungen auf dem rückseitigen Hang des verlassenen Fächers verbunden war. Am Top des Fächers ist eine Eisberg-Erosionsstruktur zu sehen. B) Nahaufnahme der feinkörnigen Ablagerungen des äußeren Fächers mit Ball- und Kissenstrukturen, die hohe Sedimentationsraten anzeigen. C) Nahaufnahme der sandigen Ablagerungen mit Kletterrippeln. Die Kletterrippeln migrieren hangaufwärts. D) Nahaufnahme der Eisberg-Erosionsstruktur am Top des Fächers. Die Erosionsstruktur ist etwa 1,5 m tief und bis zu 1,5 m breit.

core are distinctly coarse grained with relatively few sand or silt beds. Beds mainly consist of cross-bedded clast-supported pebble- to cobble-sized gravel with a fine- to coarse-grained sand matrix, which may contain scattered clasts of diamicton. Beds are often highly scoured. This coarse-grained cross-bedded upper fan gravel is interpreted to represent mouth-bar clinoforms indicating rapid deposition and progradation at an ice-marginal conduit. Deposits are texturally mature and therefore mainly represent resedimented outwash material. Slope failure and renewed sediment discharge from the tunnel mouth fed gravity flows that transported sediments radially away from the margin. Deposits of the mid-fan slope consist of massive, planar-parallel stratified, or cross-stratified pebbly sand and climbing-ripple cross-laminated sand alternating with channelized massive or normally graded gravel and pebbly sand. Towards the distal mid-fan and outer-fan slope multiple stacked climbing-ripple-cross-laminated sand units or alternations of fine-grained sand, silt, and mud occur, in which individual beds fine upwards. Scattered pebbles can frequently be observed and are mainly concentrated in mud layers. The lack of subaerial topset facies demonstrates that the retreat was probably fast and that fans did not reach the contemporary water-level (Winsemann, Asprion & Meyer 2007).

Internal deformation pattern

The deformation of the Coppenbrügge fan deposits includes both contractional and extensional structures. The lowermost fan is characterized by eastward dipping thrusts, recording glaciotectonic deformation of previously deposited ice-margin sediments (Winsemann, Asprion & Meyer 2004). Most commonly normal faults are developed. As in the Porta complex, normal faults are developed within the fan deposits and large-scale channel-fills show high-angle synsedimentary normal faults, which are parallel to the channel-margins and are interpreted as gravitational deformation (e.g., Clark & Pickering 1996, Moretti et al. 2003).

5.2 Glacial Lake Leine

The southernmost occurrences of Middle Pleistocene ice-margin deposits are recorded from the Leine and Nette Valley near Freden, Bad Gandersheim, Seesen and Bornhausen (Fig. 3), which can be related to the ice front position of the Drenthe ice sheet (e.g., Harms 1984, Thiem 1972, Feldmann 2002). These ice-marginal deposits occur over an altitude range of approximately 140–200 m a.s.l. Two subaqueous fan and delta complexes can be defined from outcrop analysis. These are the Freden subaqueous fan and delta complex and the Bornhausen delta. Deposits near Bad Gandersheim and Seesen have not been excavated in major pits and no outcrop data are available.

5.2.1 The Freden subaqueous fan and delta complex

The Freden ice-margin deposits are located on the western margin of the Leine Valley and form part of a larger ice-marginal complex that were formerly exposed in several pits between Freden and Imsen (Fig. 12). The deposits are up to 60 m thick and directly overlie Mesozoic basement rocks. Harms (1983, 1984) described a general decrease in grain size from north to south and mean palaeoflow directions towards southerly and easterly directions. Glaciotectonic deformation and the occurrence of flow till point to an ice-contact setting (Harms 1983, 1984, Feldmann & Groetzner 1998). The deposits have been mapped over an altitude range of approximately 140–200 m a.s.l. (Harms 1983, 1984) and described by several authors. Most previous workers assumed a subaerial end moraine or kame formation (e.g., Wermbter 1891, Müller 1896, von Koenen & Müller 1900, Schwarzenbach 1950, Lüttig 1954, 1960, Harms 1983, 1984, Kaltwang 1992, Latzke 1996, Feldmann & Groetzner 1998, Feldmann 2002), whereas Thome (1998) proposed a subglacial origin for the Freden deposits. A detailed work on the diagenesis of carbonate concretions within the Freden deposits has been carried out by Elbracht (2002). Clasts consist mainly of local material derived from the adjacent Mesozoic basement rocks or resedimented fluvial material, previously deposited by the Leine River. Clasts with a Scandinavian/Baltic provenance have an average proportion of 16 % and may reach up to 25 % in flow till layers (Harms 1984, Latzke 1996).

Most gravel pits have been refilled today but the large Ulrich open-pit near Freden allowed a detailed re-examination of sections (Meyer 2003, Winsemann et al. 2007, Brandes et al. 2011). Deposits formerly exposed near Imsen were described by Harms (1983, 1984). These deposits are commonly rich in gravel and associated with till layers. Palaeoflow directions are to the northeast and southeast (Fig. 12).

The Freden ice-margin deposits are exposed at an altitude of 140–173 m and are characterized by several vertically and laterally stacked moderately to steeply dipping sediment bodies, which differ in sedimentary facies, facies associations and the overall geometry. The oldest sediments are exposed in the eastern part of the open pit. Dip and palaeoflow directions are mainly towards northeasterly and southeasterly directions. The analysis of sedimentary facies indicates that these ice-margin deposits have been deposited by subaqueous gravity flows. The occurrence of ice-rafted debris and flow-till points to an ice-contact subaqueous fan setting (Winsemann et al. 2007). From this part of the section, large-scale deformation structures have also been reported (Feldmann & Groetzner 1998, Feldmann 2002), probably indicating an unstable ice margin, where short-term oscillations caused glaciotectonic deformation (Powell 1990, Lønne 1995, 2001). Upper fan deposits consist of steeply dipping (16°–20°) massive gravel deposited from cohesionless debris flows. Towards the distal upper-fan zone, intercalations of diffusely, planar-parallel, or planar cross-stratified pebbly sand increase, in-

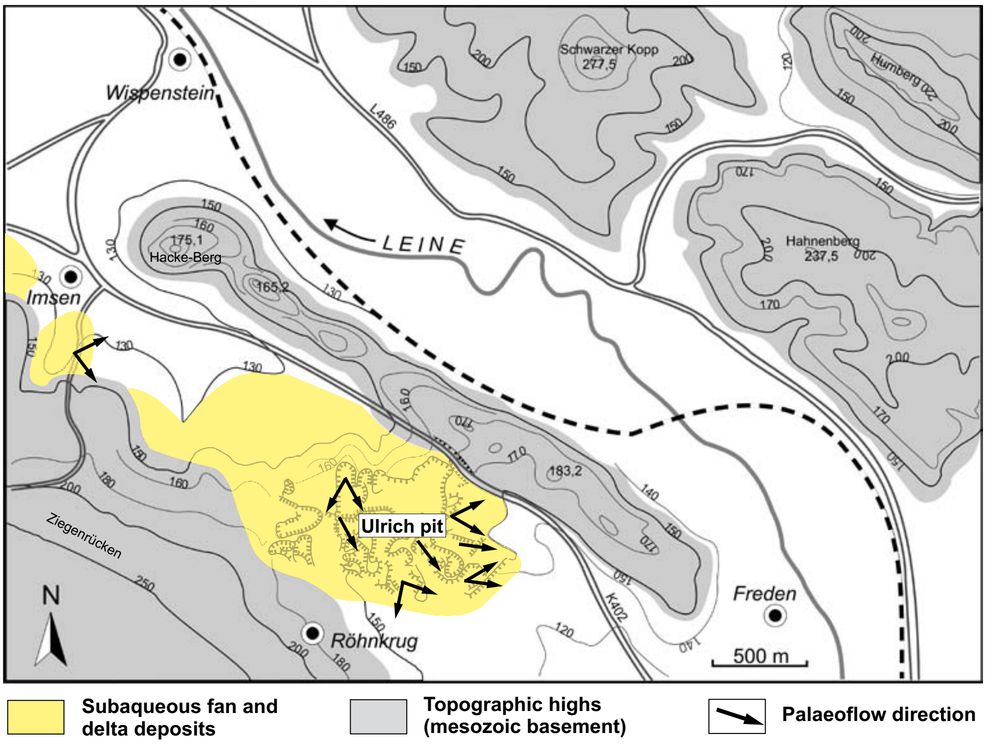

Fig. 12: Location of the Freden subaqueos fan and delta complex. Modified after Winsemann et al. (2007).

Abb. 12: Lage des Freden Fächer- und Delta-Komplexes. Verändert nach Winsemann et al. (2007).

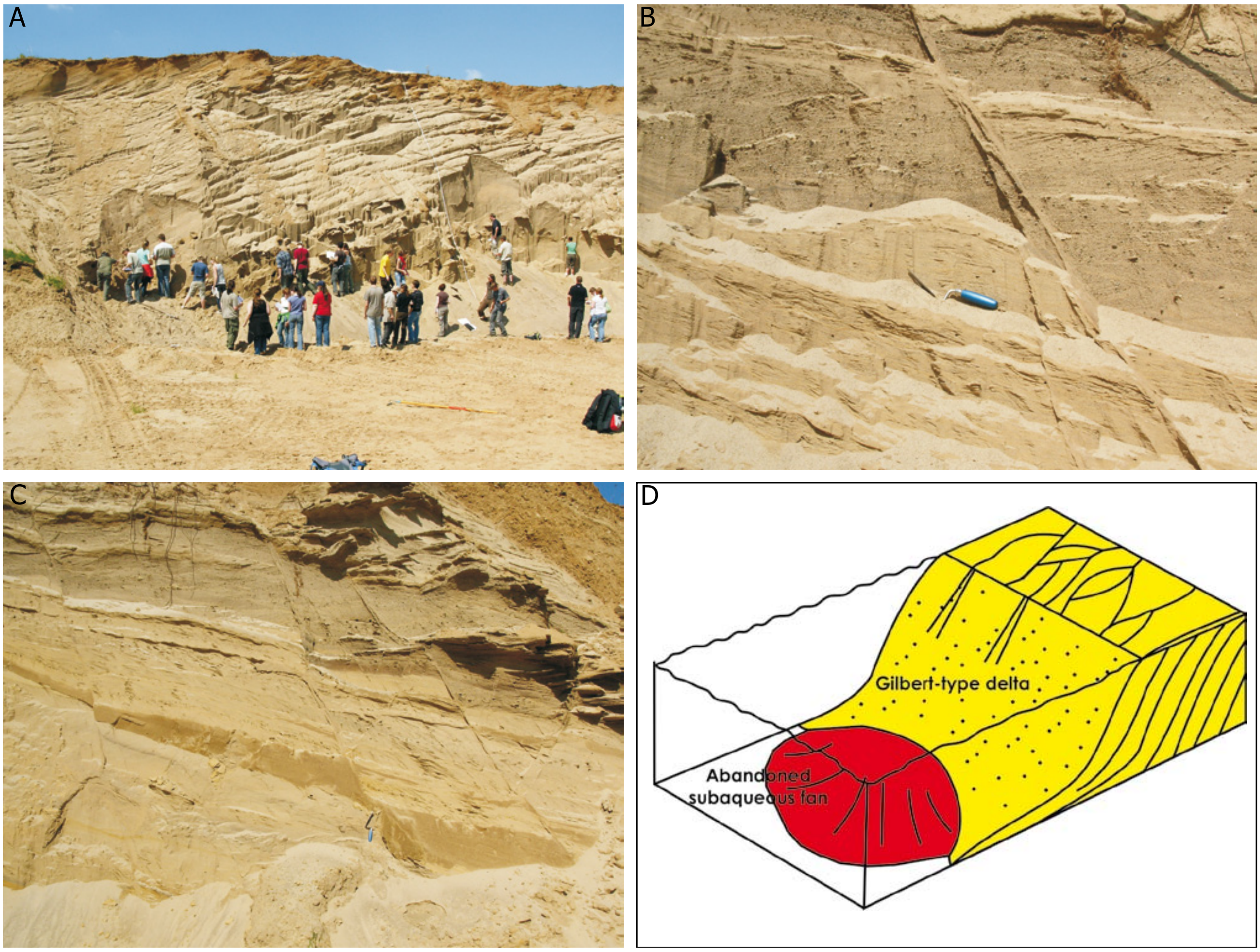

Fig. 13: Depositional architecture and sedimentary facies of the Freden subaqueous fan and delta complex. A) Steeply dipping delta foreset deposits, Ulrich pit. B) Close-up view of foreset beds, showing climbing-ripple cross-lamination and trough cross-stratification with normal deformation band faults, Ulrich pit. C) Climbing-ripple cross-laminated delta toeset deposits with normal deformation band faults, Ulrich pit. D) Depositional model of the Freden subaqueous fan and delta complex. Modified after Winsemann *et al. (2007).*

Abb. 13: Architektur und Sedimentfazies des Freden Komplexes. A) Steil einfallende Delta Foreset-Ablagerungen, Grube Ulrich. B) Nahaufnahme von Foreset-Ablagerungen mit Kletterrippeln, großdimensionierter, trogförmiger Schrägschichtung und Abschiebungen („deformation band faults"), Grube Ulrich. C) Kletterrippeln in Delta Toeset-Ablagerungen mit Abschiebungen („deformation band faults"), Grube Ulrich. D) Ablagerungsmodell für den Freden-Komplex. Verändert nach Winsemann *et al. (2007).*

dicating a change in flow regime towards more tractional deposition from sustained turbulent flows. The mid-fan deposits are characterized by moderately dipping (4°–16°) thin- to thick-bedded fine- to medium-grained massive, planar-parallel or ripple cross-laminated sand and silt beds, deposited from surge-like low-density turbidity currents.

Sediments exposed at the north-western Ulrich pit are mainly sandy and consist of planar and trough cross-stratified pebbly sand and climbing-ripple cross-laminated sand, with a large-scale tangential geometry with dip angles from 2°–30° (Fig. 13A). The sedimentary succession is up to 25 m thick and palaeoflow directions are to the southeast and southwest. High- to low-angle bedding and the occurrence of migrating bedforms indicate an upper to lower delta slope environment (e.g., Clemmensen & Houmark-Nielsen 1981, Fyfe 1990, Bornhold & Prior 1990). The supply of meltwater-transported sediment to the delta slope was from steady seasonal flows. During higher energy conditions, 2-D and 3-D dunes formed, passing downslope into ripples (Fig. 13B and C). Scours filled with deformed strata or massive or diffusely graded sand and pebbly sand record rapid cut-and-fill processes on the lower delta slope probably associated with hydraulic jumps at a break in the slope gradient. During lower flow conditions, thick climbing-ripple cross-laminated sand beds accumulated also on higher parts of the delta slope (Winsemann et. al. 2007). The delta formation is attributed to an ice-front retreat, which became stabilized in front of the mountain ridge towards the east, corresponding with the shift in palaeoflow directions towards southerly and southwesterly directions (Fig. 12). Northwestward dipping climbing-ripple cross-laminated sand beds with palaeoflow directions towards the southeast probably have been deposited on the ice-proximal back-slope of an abandoned subaqueous fan (Fig. 13 C and D). The strong progradation of delta foresets indicates a subsequent glacier stillstand and a period of high-sediment supply. The delta-foreset deposits are incised by a slope-cutting ~25 m deep NW-SE trending U-shaped channel complex, filled with large-scale cross-stratified gravel, pebbly sand and ripple cross-laminated sand, silt and mud. This channel complex probably

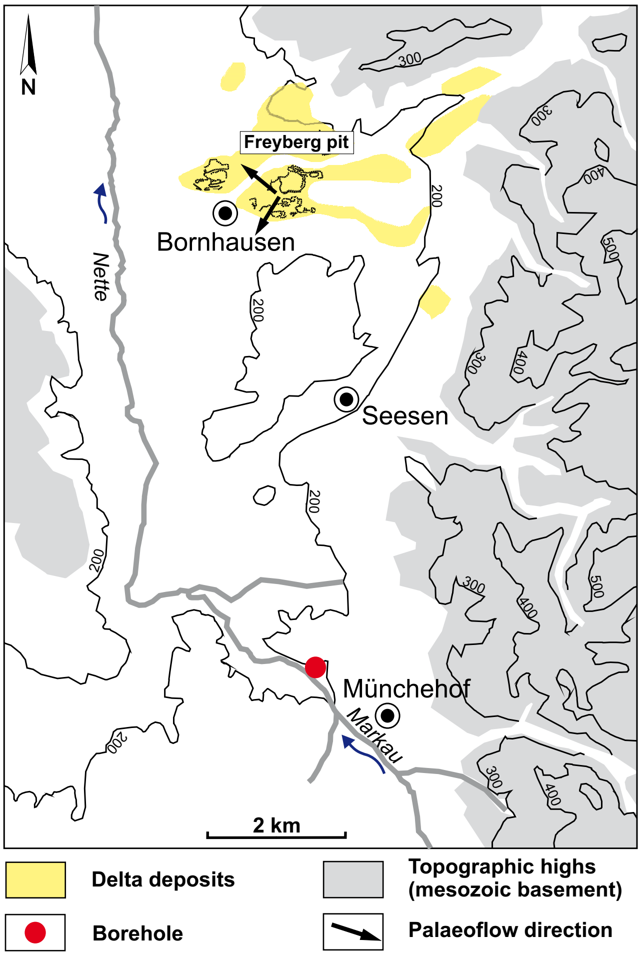

Fig. 14: Location of the Bornhausen delta. In the borehole north-west of Münchehof delta deposits of the River Markau have been drilled (Hinze 1976) indicating a lake level in the southern Nette Valley of at least 200 m a.s.l.

Abb. 14: Lage des Bornhausen Deltas. In der Bohrung nordwestlich von Münchehof wurden Delta-Ablagerungen der Markau erbohrt (Hinze 1976), die einen Seespiegel im südliche Nette-Tal von mindestens 200 m ü. NN anzeigen.

formed in response to a lake-level fall, which led to the observed entrenchment and erosion of the upper foreset and topset beds since no subaerial, glaciofluvial or distributary delta-plain components have been recognized in the exposed sections.

Internal deformation pattern

The deformation of the Freden deposits includes both contractional and extensional structures. The older subaqueous fan complex shows thrust faults, recording glaciotectonic deformation of previously deposited ice-margin sediments. Within the stratigraphic younger delta complex, numerous extensional normal faults occur (Fig. 13B and C), which have previously been related to dead-ice melting in the subsurface (Harms 1983, Feldmann 2002). New seismic and outcrop data however, indicate that these normal faults represent deformation band faults that are probably related to syn- or post-Saalian activity along basement faults (Brandes et al. 2011). These basement faults are associated with a NE-SW trending salt-cored anticline in the subsurface. In large parts of the Ulrich pit, the deformation band faults trend NW-SE, fitting to the general basement structure. Dead-ice melting can be ruled out because of the lacking concentric fault pattern. Another possible explanation is gravity-induced delta tectonics. Fault activity might also be related to salt movements and enhanced crestal collapse or to a reactivation of the basement faults due to ice loading during glaciation.

5.2.2 The Bornhausen delta

The Bornhausen ice-margin deposits are located in the Nette Valley at an altitude of 160–180 m a.s.l. (Fig. 14) and form part of a larger complex of coarse-grained meltwater deposits, occurring over an altitude range of 140–215 m a.s.l. on the eastern margin of the Nette Valley (Lüttig 1962,

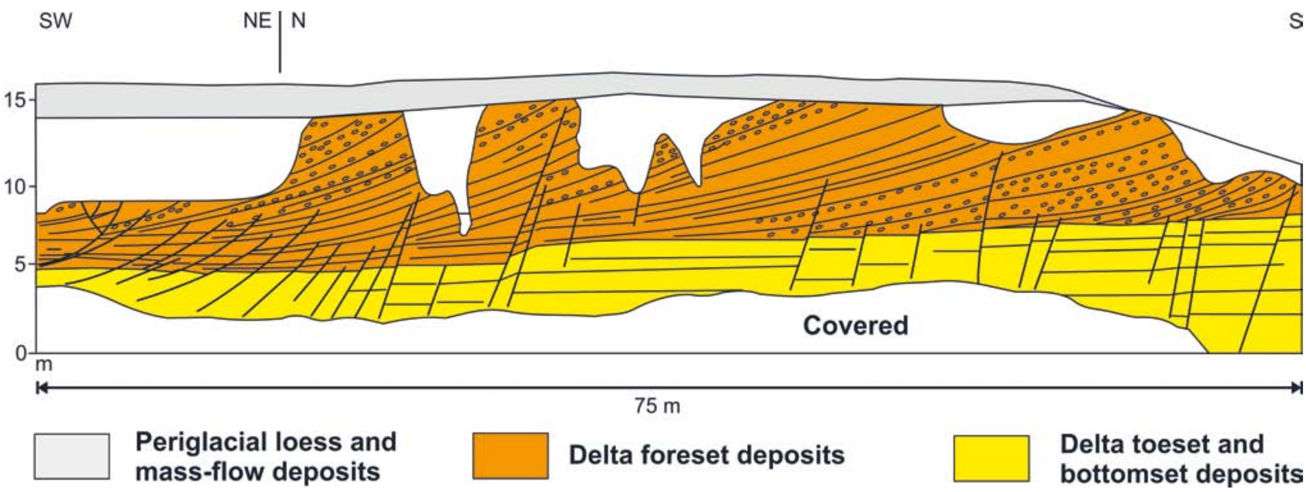

Fig. 15: Depositional architecture of the Bornhausen delta. The lower fine-grained delta toeset and bottomset deposits dip towards the south west. The overlying foreset beds steeply dip towards the north west, indicating the progradation of a new delta lobe. Note steeply north westward-dipping normal faults. Modified after Feldmann (2002) and Winsemann et al. (2007).

Abb. 15: Architektur des Bornhausen Deltas. Die unteren feinkörnigen Delta Toeset- und Bottomset-Ablagerungen fallen nach Südwesten ein. Die überlagernden gröberen Foreset-Ablagerungen fallen steil nach Nordwesten ein und zeigen die Progradation eines neuen Delta-Lobus an. Die Delta-Ablagerungen werden von steilen, nach NW einfallenden Abschiebungen durchzogen. Verändert nach Feldmann 2002 und Winsemann et al. (2007).

Hinze 1976, Bombien 1987, Feldmann 2002). These ice-marginal deposits overlie Neogene sediments and/or Middle Pleistocene till and glaciolacustrine sand and mud (Grupe & Haack 1915, Lüttig 1954, 1962, Uebersohn 1990). Palaeoflow directions indicate that meltwater flows from the north east were the main source of sediment (Bombien 1987, Feldmann 2002, Winsemann et al. 2007). Clasts consist mainly of local material derived from the adjacent Mesozoic and Palaeozoic bedrock or resedimented fluvial material, previously deposited by the Neile River (Bombien 1987). Clasts with a Scandinavian/Baltic provenance constitute ~10 % of the total (Uebersohn 1990). Several previous workers have described the outcrops, assuming a subaerial glaciofluvial formation (e.g., Grupe & Haack 1915, Lüttig 1954, 1962, Thiem 1972, Hinze 1976, Heise 1996, Uebersohn 1990, Feldmann & Groetzner 1998, Elbracht 2002, Feldmann 2002).

Most pits have been refilled today but the Freyberg pit north of Bornhausen (Fig. 14) allowed a re-examination and detailed logging of sections (Meyer 2003, Winsemann et al. 2007). The measured section is exposed at an altitude of 161–177 m a.s.l., overlying up to 5.5 m thick glaciolacustrine mud and sand (Lüttig 1962). The beds have a large-scale tangential geometry with dip angles from 10°–28°. The lowermost section consists of 3 m thick, moderately (10°–14°) southwest-dipping, very thin- to thick-bedded, massive, normally graded or climbing-ripple cross-laminated fine- to coarse-grained sand. These deposits are disconformably overlain by 12 m thick, moderately- to steeply- (12°–28°) northwestward-dipping, medium- to thick-bedded massive, normally or inversely graded or planar-parallel stratified pebbly sand, alternating with medium- to thick-bedded massive clast-supported gravel (Fig. 15).

Massive clast-supported gravel and pebbly sand with non-erosive basis or inverse distribution grading indicate deposition from cohesionless debris flows or sandy debrisflows, respectively, controlled mainly by the sediment´s frictional strength, which would explain their low mobility and steep dip (Nemec et al. 1999). The intercalation of planar-parallel stratified pebbly sand indicate deposition from sustained turbulent density flows (Kneller & Branney 1995, Plink-Björklund & Ronnert 1999, Mulder & Alexander 2001) or thin diluted sandy debris flows, generated from cohesionless subaqueous debris flows by surface flow transformation (Sohn et al. 1997, Sohn 2000, Sohn, Choe & Jo 2002). Evidence for the occurrence of flow-transformation is given by the observation that some gravel beds pass downslope into stratified pebbly sand. The finer-grained sandy material moved further downslope where it was deposited from both sustained and surge-type turbidity currents to form massive or climbing-ripple cross-laminated sand in the lower slope area. The observed disconformity in the lower section probably represents the onset of a new delta lobe progradation (Fig. 15). The sedimentary facies, high-angle tangential bedding and the absence of flow-till or ice-rafted debris points to a delta slope environment (Postma & Cruickshank 1988, Lønne 1995, Sohn et al. 1997, Falk & Dorsey 1998). However, no subaerial, glaciofluvial or distributary delta-plain components have been recognized in the exposed section

Internal deformation pattern

Within the Bornhausen deposits, numerous normal faults occur, which have offsets of several cm to dm and dip steeply north westward. The formation of these faults has been related to mass-lost in the subsurface due to salt solution or deep-rooted tectonic crestal collapse on top of the Rhüden anticline (Lüttig 1962, Übersohn 1990, Feldmann 2002). Another possible driving mechanism for the formation of these normal faults is gravitational delta tectonics or differential compaction.

6 Discussion

6.1 Depositional architecture of glaciolacustrine depositional systems

The ice marginal depositional systems of the Weserbergland and Leinebergland are characterized by coarse-grained deltas and subaqueous fans deposited from high-energy meltwater flows. The observed facies associations are consistent with previous descriptions of coarse-grained delta deposits (e.g., Clemmensen & Houmark-Nielsen 1981, Postma & Cruickshank 1988, Bornholt & Prior 1990, Nemec 1990, Lønne 1995, Sohn et al. 1997, Nemec et al. 1999) and glacigenic subaqueous fan deposits (e.g., Cheel & Rust 1982, Eyles & Clark 1988, Sharpe 1988, Sharpe & Cowan 1990, Lønne 1995, 2001, Plink-Björklund & Ronnert 1999, Russell & Arnott 2003, Bennett, Huddart & Thomas 2007, Russell, Sharpe & Bajc 2007). The sedimentary facies, morphology, and extent of ice-marginal deposits indicate deposition into proglacial lakes at the margin of a temperate lobate, grounded ice sheet (e.g., Ashley, Boothroyed & Borns 1991). The groundling line of temperate glaciers is the one where the largest volume of sediment is deposited and large quantities of glaciofluvial bedload and suspended load can be transported and deposited by jets (Powell & Domack 1995). In glaciolacustrine environments, sediment-laden meltwater is generally denser than the surrounding lake water, and will tend to produce underflows (Fig. 16 A). Deposition on grounding line subaqueous fans is therefore likely to be dominated by gravity flows, with comparatively minor inputs from high-level suspended sediment (Benn & Evans 1998). If the ice terminus remains stable for a long period of time, a grounding line fan may aggrade to lake level and form an ice-contact/glaciofluvial delta (Powell 1990, Lønne, 1995).

The position of ice marginal fans and deltas in the study area was controlled by the combination of bedrock topography and water depth. Correspondingly depositional processes and the resulting facies architecture of depositional systems are highly variable. The delta complexes reflect a relatively stable position of the ice-margin in front of mountain ridges or major basement highs (Fig. 16 B). Subaqueous fans commonly reflect more unstable icefronts of smaller ice-lobes that advanced into the lake basins and were subject to periodic calving and short-term oscillations (e.g., Fowler 1987, Fyfe 1990, Powell 1990, Powell & Domack 1995).

The ice-marginal deposits of glacial Lake Weser and glacial Lake Leine mainly record the sedimentation dur-

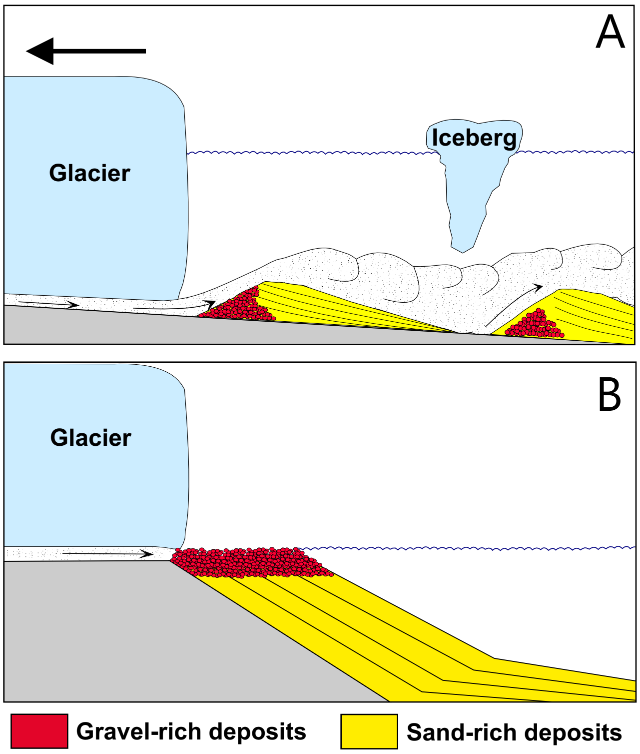

Fig. 16: Schematic model of glaciolacustrine ice-margin deposits. A) Depositional architecture of subaqueous ice-contact fans during ice-margin retreat. B) Depositional architecture of a glaciofluvial Gilbert-type delta. Modified after Powell (1990) and Lønne (1995).

Abb. 16: Schematisches Ablagerungsmodell für glazilakustrine Eisrand-Systeme. A) Schematisches Modell eines subaquatischen Eiskontaktfächers während eines Eisrückzugs. B) Schematisches Modell eines glazifluviatilen Gilbert-Deltas. Verändert nach Lønne (1995) and Powell & Domack (1995).

ing ice-sheet retreat. This is most likely because proglacial deposits are commonly overridden and incorporated into the base of the ice during ice advance (Ashley 1995). After a phase of maximum ice-advance, accompanied by the deposition of ice-contact subaqueous fan deposits and deformation of fan deposits, a rapid back-stepping of fan bodies towards up-slope positions occurred. Individual fan bodies commonly have a coarse-grained core of flat-lying to steeply dipping gravel, overlain by fining-upward packages of gravel, sand and mud (Fig. 16A). During ice-margin retreat, often rhythmically laminated fine-grained sediments rich in ice-rafted debris were deposited on both the ice-distal and ice-proximal slopes of the abandoned fans. Climbing-ripple cross-laminated sand may onlap coarse-grained upper fan gravel and in some cases overtop the older fan deposits (Fig. 11).

Ice-margin retreat was probably caused by an overall lake level rise. Bedrock highs acted as pinning points for the retreating ice lobes and after the re-establishment of the subglacial drainage systems, ice-marginal sediment accumulated from restricted point sources, giving rise to small isolated subaqueous fans. Smaller conduits are more unstable and have smaller effluxes, which more easily mix with lake water, so constraining the distance of sediment dispersal (Fyfe 1990, Sharpe & Cowan 1990). The lack of subaerial topset facies demonstrates that the retreat was fast and fans did not reach the contemporary water-level (Lønne 1995).

The large size of the northernmost Porta fan system (fan III, Fig. 5 and Fig. 6) is attributed to the position in front of the Porta Westfalica pass, where a stable meltwater tunnel facilitated the construction of a larger subaqueous fan. The dimension of jet-efflux deposits is much larger than that of previously described examples from the Laurentide Ice Sheet (e.g., Gorrell & Shaw 1991, Russell & Arnott 2003) and the frequent occurrence of tractive structures in gravelly and sandy fan deposits indicates sustained and high-energy flows associated with high discharges (Powell 1990, Lønne 1995, Cutler, Colgan & Mickelson 2002).

When the retreating ice lobes stabilized in front of mountain ridges, subaqueous ice-contact fans could build-up to the lake-level and evolve into ice-contact deltas/glaciofluvial deltas as observed in the Freden subaqueous fan and delta complex (Fig. 12 and Fig. 13D). In the Weser Lake, strong lake-level falls led to a widespread truncation of subaqueous fan deposits, which partly became overlain by delta deposits (Fig. 7).

6.2 Deformation structures

The observed deformation structures within the ice-marginal deposits mainly consist of normal faults and deformation band faults. The occurrence of normal faults in ice-marginal deposits is commonly related to mass-loss due to dead ice-melting (e.g., Selsing 1981, Harms 1983, Prange 1995, Juschus 2003). However, re-examination of tectonic deformation structures by Brandes, Polom & Winsemann (2011) and Brandes et al. (2011) indicate that this extensional deformation was most probably caused by other mechanisms such as gravity induced delta tectonics, crestal collapse above salt domes and a reactivation of basement faults due to ice and water loading/unloading.

The strong influence of ice-loading on the regional seismicity was shown by several authors (e.g., Dehls et al. 2000, Fjeldskaar et al. 2000, Stewart, Sauber & Rose 2000) and a reactivation of normal faults caused by lake formation was documented for the Wasatch Fault in the western U.S. (Hetzel & Hampel, 2005). In our study area the lithosphere was effected by i) the growth and decay of the Drenthe ice-sheet and associated proglacial lakes and ii) local sediment loading by thick ice-marginal deposits. It is very likely that the basement coupled deformation in the study area was caused by the advance of the Drenthe ice sheet (Brandes, Polom & Winsemann 2011). The interplay of ice sheet and tectonic structures in northern Germany was previously discussed by Reicherter, Kaiser & Stackebrandt (2005) and described by Adams (1989), Liszowski (1993) and Stewart, Sauber & Rose (2000) from Canada, Poland and Scandinavia, respectively. The flexure of the lithosphere due to glacial loading created a compressive stress at the front of the ice sheet and the fore-bulge area was characterized by uplift and extension as described in the model of Stewart, Sauber & Rose (2000). The advance of the ice-sheet induced a transfer of the stress-front through the upper lithosphere and pre-existing basement faults were probably reactivated due to the varying stress conditions. The Triassic-Jurassic normal faults trend WNW-ESE parallel to the Saalian ice-margin (Fig. 9). They were in an ideal position for a reactivation due to the extensional stress field in the foreland of the glacier because the orientation of the glacier induced stress field matches the orientation of the palaeo-stress field. The growth of the ice-marginal deltas and subaqueous fans created a local load that might have enhanced the reactivation of normal faults in the basement. The water pressure could have reduced the friction along the faults and supported the slip process. Sirocko et al. (2002, 2008) described young halokinetic movements in northern Germany, related to salt diapirs. Salt structures in the study area are present below the Freden and Bornhausen ice-margin deposits. In this case, salt tectonics may have played an important role. Though a reactivation of pre-existing basement faults and salt structures due to loading and related effects is very likely, a neotectonic component cannot be ruled out.

6.3 Influence of Saalian proglacial lakes on ice sheet dynamics

The formation of proglacial lakes may exert an important influence on ice sheets. Calving speed in fresh water scales linearly with water depth and exponentially with ice temperature (Warren, Greene & Glasser 1995). Progressive deepening of lakes therefore, may lead to an increased removal of ice through calving and an increase of subglacial water pressure proximal to the ice (Cutler et al. 2001, Winsborrow et al. 2010). Compared to adjacent areas of ice sheet terminating on dry land, this would have the effect of reducing the basal shear stress and an increase in ice velocity up-ice from the lake (Stokes & Clarke 2004).

We assume that the formation and catastrophic drainage of deep proglacial lakes in front of the Drenthe ice sheet considerably influenced the ice-sheet stability and may have initiated the Hondsrug ice stream. The Drenthe glaciation in the study area is characterized by three different ice-advances (e.g., van den Berg & Beets 1987, KLostermann 1992, Skupin, Speetzen & Zandstra 1993, 2003). The first ice advance had a southerly to slightly southeasterly direction (Skupin, Speetzen & Zandstra 1993, Ehlers et al. 2004) and blocked the northward drainage pathway of the Weser River and Leine River, leading to the incipient formation of proglacial lakes in front of the Drenthe ice-sheet. During this ice advance, the Leine Lake basin was completely blocked whereas the Weser Lake could probably still drain southwestward along the Teutoburger Wald Mountains (e.g., Klostermann 1992). The maximum ice extent in the Upper Weser and Leine Valley was reached and the lower portions of the Porta, Coppenbrügge, and Freden complex were probably deposited.

From the Netherlands and northwestern Germany a second southwestward-directed ice advance is recorded (van den Berg & Beets 1987, Skupin, Speetzen & Zandstra 1993, 2003, Ehlers et. al. 2004). During this ice advance, an ice lobe intruded into the Münsterland Embayment and the valley between the Teutoburger Wald Mountains and Wiehengebirge Mountains, leading to the successive closure of lake overspill channels in the Teutoburger Wald Mountains (Thome 1983, Klostermann 1992, Skupin, Speetzen & Zandstra 1993, 2003). The closure of these overspill channels caused the observed long-term transgression of the Weser Lake. As a consequence the ice lobes within the northernmost Weser Valley rapidly collapsed and a new ice margin became stabilized in front of the Wesergebirge Mountains (Winsemann et. al. 2007). At the western lake margin, ice-marginal deposits (Markendorf delta, Ravensberger Kiesssandzug) became deformed and overridden (Skupin, Speetzen & Zandstra 2003).

At the easternmost Münsterland Embayment, a proglacial lake formed in front of the Münsterland ice lobe (Thome 1998, Herget 1998). This lake is referred to as “glacial Lake Paderborn” (Thome 1998) or “glacial Lake Münsterland” (Meinsen et al., in press), respectively. During highstand, the lake had a maximal lake level of ~350 m a.s.l. (Herget 1998) and probably a maximum depth of up to ~170 m (Meinsen et al. in press). The lake drained southwestwards into the Möhne and Ruhr valley through outlet channels, located at the southwestern lake margin (Thome 1983, 1998, Herget 1998).

The progressive deepening of lakes in the Münsterland Embayment and Upper Weser Valley probably led to an increased removal of ice through calving, a rapid retreat of the western ice-lobes and opening of the 135 m a.s.l. and 95m a.s.l. overspill channels in the Teutoburger Wald Mountains. During the subsequent Weser Lake outburst floods, 110 km^3 of water was released into the Münsterland Embayment and the lake level of the Weser Lake dropped by as much as 100 m (Fig. 4). These two outburst floods must have led to an increase in the ice temperature due to frictional heating and enhanced melting and rapid destabilization of the Münsterland ice lobe (Meinsen et al. in press). Subsequently, an ice re-advance occurred, leading to the renewed closure of the 95 m a.s.l. overspill channel and a related lake-level rise of glacial Lake Weser (Fig. 4). This ice-advance is related to the Hondsrug ice stream (van den Berg & Beets 1987, Passchier et al. 2010), which is the last ice advance recorded from the Münsterland Embayment (Skupin, Speetzen & Zandstra 1993). We speculate that the Hondsrug ice stream may have been enhanced or even triggered by the combination of glacial lake formation in the Münsterland Embayment and outburst floods of glacial Lake Weser. The associated removal of ice may have led to a rapid draw-down of ice, triggering fast ice flow (Stokes & Clark 2004, Winsborrow et al. 2010).

After the drainage of glacial Lake Weser and glacial Lake Münsterland the Hondsrug ice stream advanced into the Münsterland Embayment, probably considerably thinning the ice sheet profile in this region. The splayed, lobate pattern of the Hondsrug ice stream (van den Berg & Beets 1987, Skupin, Speetzen & Zandstra 1993) indicates that it probably terminated on dry land or discharged into very shallow water. Stokes & Clark (2004) pointed out that once achieved, the calving processes and losses might play a secondary role in the functioning of an ice stream and once rapid basal sliding is established thermomechanical feedback mechanism may sustain fast ice flow. Subsequently the thinned Drenthe ice sheet deglaciated rapidly (van den Berg & Beets 1987, Passchier et al. 2010).

6.4 Implications for the position of the Elsterian ice-margin and associated proglacial lakes

The position of the Elsterian ice-margin in the study area is unclear and several reconstructions of the Elsterian ice-margin have assumed a glacial advance into the Upper Weser and Upper Leine Valley (e.g., Liedtke 1981, Jordan & Schwartau 1993, Klostermann 1995, Thome 1998, Feldmann 2002, Ehlers et. al. 2004).

The assumption of a farther southward reaching Elsterian ice-margin is based on

1. the occurrence of scattered erratic clasts beyond the Saalian ice-margin (e.g., Waldeck 1975, Jordan 1994)
2. the occurrence of reworked erratic clasts in Middle Pleistocene fluvial deposits (e.g., Rohde & Thiem 1998).

Based on this study, it seems more likely that scattered erratic clasts beyond the Saalian ice-margin represent ice-rafted debris dumped from icebergs rather than being relics of reworked Elsterian deposits. Middle Pleistocene fluvial deposits with reworked erratic clasts might represent Saalian deposits that formed in response to temporal glacial lake formation and rapid lake drainage. We therefore assume that all ice-marginal sediments of the Weserbergland- and Leinebergland have been deposited into the Saalian proglacial lakes. A Saalian age of these ice-marginal deposits is also assumed in new geological maps (1: 50 000) of the LBEG.

Thome (1998) proposed the existence of even larger glacial lakes in the Upper Weser and Leine Valley during the Elsterian glaciation. He argued that glacial Lake Weser stood at a level of 300 m a.s.l., controlled by the altitudes of potential outlet channels. Since there is no evidence that the Elsterian ice margin did reach farther south westward than the Saalian Drenthe ice sheet, it is not very likely that a large lake was dammed in the Upper Weser Valley because the water would have probably drained along the Teutoburger Wald Mountains. The examination of more than 2000 borehole logs in the Upper Weser Valley gave no evidence for the existence of older pre-Saalian glacial lake sediments. However, fluvial erosion might have led to a complete removal of older deposits.

The existence of a larger Elsterian proglacial lake in the Upper Leine Valley is more likely because the Leine Valley has less potential lake outlets and the thick accumulation of fine-grained lake deposits may also contain older Elsterian deposits (e.g., Jordan 1984, 1986).

7 Conclusions

The re-examination of Middle Pleistocene ice-marginal deposits in the Weser- and Leinebergland reveal that these deposits consists of ice-contact deltas and subaqueous fans deposited from high-energy meltwater flows into large and deep proglacial lakes.

▪ Based on the new interpretation of ice-marginal depositional systems, lake-levels of approximately 200 m a.s.l. must be considered for both glacial Lake Weser and glacial Lake Leine during the Saalian Drenthe glaciation.

▪ The geometry and sedimentary facies of subaqueous fan and delta deposits indicate deposition into proglacial lakes at the margin of the retreating ice sheet. The position of ice marginal fans and deltas was controlled by the combination of bedrock topography and water depth. During ice-lobe retreat, bedrock highs served as pinning points whereas a flat-bottom topography caused a more rapid ice wastage because the ice terminated in deeper water and the calving rate may have exceeded the ice flux, resulting in rapid retreat.

▪ Subaqueous fans formed where glaciofluvial detritus were carried to the lake via tunnels near or at the base of an ice cliff, commonly associated with an unstable ice-front. Individual fan bodies have a coarse-grained proximal core of flat-lying to steeply-dipping gravel, overlain by sand-rich mid- to outer-fan deposits. During glacier retreat, fine-grained sediments were deposited on the ice-distal and ice-proximal slopes of the abandoned fans. During lake-level fall, the subaqueous fan systems emerged and were partly overlain by delta deposits.

▪ The formation of delta complexes reflects a relatively stable position of the ice-margin in front of mountain ridges or major basement highs that acted as pinning points. The sedimentary facies and depositional architecture of ice-marginal deltas resemble those of non-glacial Gilbert-type deltas, except for the deposition of glacial debris.

▪ The observed deformation structures within the ice-marginal deposits comprise both contractional and extensional features. Contractional structures are related to glaciotectonic processes. However, most commonly normal faults and deformation band faults are developed. Different driving mechanisms caused this extensional deformation including gravity induced delta tectonics, crestal collapse above salt domes and a reactivation of basement faults due to ice and water loading and unloading. In some cases, a neotectonic component cannot be ruled out. Dead-ice melting, however, did not play a major role.

▪ We hypothesise that the formation of deep proglacial lakes in the study area considerably influenced the stability of the southern Drenthe ice sheet and prevented a farther southward ice advance into the Upper Weser and Leine Valley by an increased removal of ice through calving.

▪ We speculate that the Hondsrug ice stream may have been enhanced or even triggered by the combination of glacial lake formation in the Münsterland Embayment and outburst floods of glacial Lake Weser. The associated removal of ice may have led to a rapid draw-down of ice, triggering fast ice flow and deglaciation.

▪ Based on our valley-fill analysis, it seems unlikely that the Elsterian ice sheet reached farther south than the Saalian Drenthe ice sheet in the study area.

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9 References

Adams, J. (1989): Postglacial faulting in eastern Canada: nature, origin and seismic hazard implications. – Tectonophysics, 163: 323–331.

Ashley, G. M. (1995): Glaciolacustrine Environments. – In: Menzies, J. (ed.): Modern Glacial Environments: 417–444; Oxford (Butterworth-Heinemann).

Ashley, G.M., Boothroyed, J.C. & Borns, H.W., Jr. (1991): Sedimentology of late Pleistocene (Laurentide) deglacial-phase deposits, eastern Maine; an example of a temperate marine grounded ice sheet margin. – In: Ashley J.B. & Ashley G.M. (eds.): Glacial Marine Sedimentation, Paleoclimatic Significance. – Geological Society of America Special Paper, 261: 107–125.

Attig, K. (1965): Das Quartär südöstlich der Porta Westfalica unter besonderer Berücksichtigung der glaziofluviatilen Sedimente. – 43 S., unpublished diploma thesis; University of Braunschweig.

Benn, D.I. & Evans, D.J.A. (1998): Glaciers & Glaciation. – 734 S.; London (Arnold).

Bennett, M.R., Huddart D. & Thomas, G.S.P. (2007): The Newbigging esker system, Lanarkshire, southern Scotland: a model for composite tunnel, subaqueous fan and supraglacial esker sedimentation. – In: Hambrey, M., Christoffersen, P., Glasser N & Hubbard, B. (eds.): Glacial Processes and Products. – IAS Specical Publications, 39: 177–202.

Bilotti, F. & Shaw, J.H. (2005): Deep-water Niger delta fold and thrust belt modelled as a critical –taper wedge: the influence of elevated basal fluid pressure on structural styles. AAPG Bulletin, 89: 1475–1491.

Blum, M.D. & Törnqvist, T.E. (2000): Fluvial responses to climate and sea-level change: a review and look forward. – Sedimentology, 47 (Suppl. 1): 2–48.

Bombien, H. (1987): Geologisch-petrographische Untersuchungen zur quartären (früh-Saale-zeitlichen) Flußgeschichte im nödlichen Harzvorland. – Mitteilungen aus dem Geologischen Institut der Universität Hannover, 26: 1–131.

Bornhold, B.D. & Prior, D.B. (1990): Morphology and sedimentary processes on the subaqueous Noeick River delta, British Columbia, Canada. – In: Colella, A. & Prior, B.D. (eds.): Coarse-Grained Deltas. – IAS Specical Publications, 10: 169–181.

Brandes, C., Polom, U. & Winsemann, J. (2011): Reactivation of basement faults: interplay of ice-advance, glacial lake formation and sediment loading. – Basin Research, 23: 53–64. Doi: 10.1111/j.1365 –2117.2010.00465.x.

Brandes, C., Tanner, D., Polom, U. & Winsemann, J. (2011): Deformation bands in Pleistocene sediments related to basement tectonics. – Geophysical Research Abstracts, EGU Meeting 2011, Wien.

Busschers, F.S., Van Balen, R.T., Cohen, K.M., Kasse, C., Weerts, H.J.T., Wallinga, J. & Bunnik, F.P.M. (2008): Response of the Rhine –Meuse fluvial system to Saalian ice-sheet dynamics. – Boreas, 37: 377–398.

Carling, P.A., Kirkbride, A.D., Parnachov, S., Borodavko, P.S. & Berger, G.W. (2002): Late Quaternary catastrophic flooding in the Altai Mountains of south-central Siberia: a synoptic overview and an introduction to flood deposit sedimentology. – In: Martini, P.I., Baker, V.R. & Garzon, G. (eds.): Flood and Megaflood Processes and Deposits: Recent and Ancient Examples. – IAS Specical Publications, 32: 17–35.

Caspers, G., Jordan, H., Merkt, J., Meyer, K.-D., Müller, H. & Streif, H. (1995): III. Niedersachsen. – In: Benda, L. (ed.): Das Quartär Deutschlands: 23–58; Berlin (Gebr. Bornträger).

Cheel, R.J. & Rust, B.R. (1982): Coarse grained facies of glaciomarine deposits near Ottawa, Canada. – In: Davidson-Arnott, R. Nickling W. & Fahey B.D. (eds.): Research in Glaciofluvial and Glaciolacustrine Systems: 279–295. Norwich (Geo Books).

Clark, J.D. & Pickering, K.T. (1996): Architectural elements and growth pattern of submarine channels: application to hydrocarbon exploration. – AAPG Bulletin, 80: 194–221.

Clemmensen, L.B. & Houmark-Nielsen, M. (1981): Sedimentary features of a Weichselian glaciolacustrine delta. – Boreas, 10: 229–245.

Colman, S.M., Clark, J.A., Clayton, L., Hansel, A.K. & Larsen, C.E. (1994): Deglaciation, lake levels, and meltwater discharge in the Lake Michigan Basin. – Quaternary Science Reviews, 13: 879–890.

Cutler, P.M., Mickelson, D.M., Colgan, P.M., MacAyeal, D.R. & Parizek, B.R. (2001): Influence of the Great Lakes on the dynamics of the southern Laurentide ice sheet: Numerical experiments. – Geology, 29: 109–1042.

Cutler, P.M., Colgan, P.M. & Mickelson, D.M. (2002): Sedimentologic evidence for outburst floods from the Laurentide Ice Sheet margin in Wisconsin, USA: implications for tunnel-channel formation. – Quaternary international, 90: 23–40.

Dehls, J.F., Olesen, O., Olsen, L. & Blikra, L.H. (2000): Neotectonic faulting in northern Norway; the Stuoragurra and Nordmannvikdalen postglacial faults. – Quaternary Science Reviews, 19: 1447–1460.

Deters, H.-B. (1999): Internbau und Genese von zwei pleistozänen Kies-Sand-Vorkommen östlich von Hameln (Afferde, Coppenbrügge) im Niedersächsischen Bergland. – 100 S.; unpublished diploma thesis; University of Hannover.

Deutloff, O., Kühn-Velten, H., Michel, G., & Skupin, K. (1982): Erläuterungen zu Blatt C3918 Minden, Geologische Karte von Nordrhein -Westfalen 1: 100 000. – 80 S.; Krefeld.

Driever, E. (1921): Die Entwicklung des Längstales Porta-Osnabrück. – Jahresberichte des naturwissenschaftlichen Vereins Osnabrück, 18: 1–88.

Ehlers, J., Eissmann, L., Lippstreu, L., Stephan, H.-J. & Wansa, S. (2004): Pleistocene glaciations of North Germany. – In: Ehlers, J., Gibbard, P. (eds.): Quaternary Glaciations. Extent and Chronology Part I, Europe: 135–146; Amsterdam (Elsevier).

Eissmann, L. (1997): Das quartäre Eiszeitalter in Sachsen und Nordostthüringen. – Altenburger Naturwissenschaftliche Forschung, 8: 1–98.

Eissmann, L. (2002): Quaternary geology of eastern Germany (Saxony, Saxon –Anhalt, South Brandenburg, Thüringia), type area of Elsterian and Saalian Stages in Europe. – Quaternary Science Reviews, 21: 1275–1346.

Elbracht, J. (2002): Karbonatische Zementation pleistozäner Lockersedimente in NW-Deutschland. – 111 S.; unpublished doctoral thesis, University of Hannover.

Eyles, N. & Clark, B.M. (1988): Storm-influenced deltas and ice scouring in a late Pleistocene glacial lake. – GSA Bulletin, 100: 793–809.

Falk, P.D. & Dorsey, R.J. (1998): Rapid development of gravely high –density turbidity currents in marine Gilbert-type fan deltas, Loreto basin, Baja California Sur, Mexico. – Sedimentology, 45: 331–349.

Farrenschon, J. (1995): Erläuterungen zu Blatt 4020 Blomberg, Geologische Karte von Nordrhein-Westfalen 1: 25 000. – 155 S.; Krefeld.

Feldmann, L. (2002): Das Quartär zwischen Harz und Allertal mit einem Beitrag zur Landschaftsgeschichte im Tertiär. – Clausthaler Geowissenschaften, 1: 1–149.

Feldmann, L. & J.-P. Groetzner (1998): Leinebergland und nördliches Harzvorland. – In: Feldmann, L. & Meyer, K.D. (eds.): Quartär in Niedersachsen. Exkursionsführer zur Jubiläums-Hauptversammlung der Deutschen Quartärvereinigung in Hannover, Exkursion B: 37-88; Hannover.

Fjeldskaar, W., Lindholm, C. Dehls, J.F. & Fjeldskaar, I. (2000): Postglacial uplift, neotectonics and seismicity in Fennoscandia. – Quaternary Science Reviews, 19: 1413–1422.

Fowler, A.C. (1987): Sliding with cavity formation. – Journal of Glaciology, 33: 255–267.

Fyfe, G. (1990): The effects of water depth on ice-proximal glaciolacustrine sedimentation: Salpausselkä I, southern Finland. – Boreas, 19: 147–164.

Gorell, G. & Shaw, J. (1991): Deposition in an esker, bead and fan complex, Lanark, Ontario, Canada. – Sedimentary Geology, 72: 285–314.

Groetzner, J.-P. (1995): Central Upland Traverse, 9th day. – In: Schirmer, W. (ed.): Quaternary Field Trips in Central Europe: 588–590; 14th International INQUA Congress Berlin; München (Dr. Friedrich Pfeil).

Grupe, O. & Haack, W. (1915): Erläuterungen zu Blatt 4026 Lamspringe, Geologische Karte von Preußen und benachbarten Bundesstaaten 1: 25 000. – 80 S.; Berlin.

Grupe, O. (1926): Tal- und Terrassenbildung im Gebiete der Werra-Fulda-Weser und Soergels „Gliederung und absolute Zeitrechnung des Erdzeitalters“. – Geologische Rundschau, 17: 161–196.

Grupe, O. (1930): Die Kamesbildungen des Weserberglandes. – Jahrbuch der Preußischen Geologischen Landes-Anstalt, 51: 350–370.

Grupe, O., Koert, W. & Stach, E. (1933): Erläuterungen zu Blatt 3719 Minden, geologischen Karte von Preussen und benachbarter deutscher Länder 1: 25 000. – 67 S., Berlin.

Harms, F. –J. (1983): Zur Geologie saalezeitlicher Sedimente am Rande des Leinetals zwischen Imsen und Freden. – Beiträge zur Naturkunde Niedersachsens, 36, Jahrgang 2: 53–69.

Harms, F.–J. (1984): Erläuterungen zu Blatt Nr. 4025 Freden, Geologische Karte von Niedersachsen 1: 25 000. – 168 S.; Hannover.

Heise, K. (1996): Petrographische Zusammensetzung und Alter von Kleinvorkommen glaziärer Sedimente im NW Harzvorland. – 52 S.; unpublished diploma thesis; University of Hannover.

Herget, J. (1998): Temporäre Entwässerungsbahnen am Südrand der Westfälischen Tieflandsbucht – ein Szenario. – In: Glatthaar, D. & Herget, J. (eds.): Physische Geographie und Landeskunde – Festschrift für Herbert Liedtke. – Bochumer Geographische Arbeiten Sonderreihe, 13: 23–30.

Herrmann, R. (1958): Eisrandablagerungen und Fließerden am Nordrand des Leineberglandes. – Geologisches Jahrbuch, 76: 309–320.

Hesemann J. (1975): Geologie Nordrhein-Westfalens. – 416 S.; Paderborn (Ferdinand Schöningh).

Hetzel, R. & Hampel, A. (2005): Slip rate variations on normal faults during glacial-interglacial changes in surface loads. – Nature, 435: 81–84.

Hinze, C. (1976): Erläuterungen zu Blatt Seesen Nr. 4127, Geologische Karte von Niedersachsen 1: 25 000. – 161 S.; Hannover.

Hornung, J.J., Asprion, U. & Winsemann, J. (2007): Jet-efflux deposits of a subaqueous ice-contact fan, glacial Lake Rinteln, northwestern Germany. – Sedimentary Geology, 193: 167–192.

Jarek, M. (1999): Kartierung und Faziesanalyse der Emme: Ein drenthezeitlicher Deltakomplex am Südhang des Wesergebirges. – 66 S.; unpublished diploma thesis; University of Hannover.

Johnsen, T. F. & Brennand, T.A. (2006): The environment in and around ice-dammed lakes in the moderately high relief setting of the southern Canadian Cordillera. – Boreas, 35: 106–125.

Jordan, H. (1984): Erläuterungen zu Blatt Nr. 4325 Nörten-Hardenberg, Geologische Karte von Niedersachsen 1: 25 000. – 146 S.; Hannover.

Jordan, H. (1986): Erläuterungen zu Blatt Nr. 4225 Northeim West, Geologische Karte von Niedersachsen 1: 25 000. – 144 S.; Hannover.

Jordan, H. (1989): Geologische Wanderkarte Leinebergland 1: 100 000. – Hannover.

Jordan, H. (1993): Erläuterungen zu Blatt Nr. 4125 Einbeck, Geologische Karte von Niedersachsen 1: 25 000. – 107 S.; Hannover.

Jordan, H. (1994): Erläuterungen zu Blatt Nr. 4024 Alfeld, Geologische Karte von Niedersachen 1: 25 000. – 126 S.; Hannover.

Jordan H. & Schwartau, W. (1993): Das Lößprofil von Ahlshausen und weitere tiefe Quartäraufschlüsse entlang der Bundesbahn-Neubaustrecke bei Northeim, Südniedersachen. – Eiszeitalter und Gegenwart, 43: 110–122.

Junge, F.W. (1998): Die Bändertone Mitteldeutschlands und angrenzender Gebiete. – Altenburger Naturwissenschaftliche Forschung, 9: 1–210.

Juschus, O. (2003): Das Jungmoränenland südlich von Berlin – Untersuchungen zur jungquartären Landschaftsentwicklung zwischen Unterspreewald und Nuthe. Berliner Geographische Arbeiten, 95: 1–152.

Kaltwang, J. (1992): Die pleistozäne Vereisungsgrenze im südlichen Niedersachsen und im östlichen Westfalen. – Mitteilungen aus dem Geologischen Institut der Universität Hannover, 33: 1–161.

Klostermann, J. (1992): Das Quartär der Niederrheinischen Bucht – Ablagerungen der letzten Eiszeit am Niederrhein. – 200 S.; Krefeld (Geologisches Landesamt Nordrhein-Westfalen).

Klostermann, J. (1995): IV. Nordrhein-Westfalen. – In: Benda, L. (ed.): Das Quartär Deutschlands: 59–94; Berlin (Gebr. Bornträger).

Kneller, B.C. & Branney, M.J. (1995): Sustained high-density turbidity currents and the deposition of thick massive sands. – Sedimentology, 42: 607–616.

Koenen, A. v. & Müller, G. (1900): Erläuterungen zu Blatt 4025 Gross-Freden, Geologische Specialkarte von Preussen und den Thüringischen Staaten 1: 25000. – 28S.; Berlin.

Koken, E. (1901): Beiträge zur Kenntnis des schwäbischen Diluviums. – Neues Jahrbuch für Mineralogie, Geologie und Paläontologie, Beilagen-Band, 14: 120–170.

Könemann, P. (1995): Der Sand- und Kiesabbau im Wesertal an der Porta Westfalica – Ökonomische und ökologische Untersuchungen zur Belastung und Inwertsetzung des Naturraumpotentials. – Hannoversche Geographische Arbeiten, 50: 1–216.

Kulle, S. (1985): Drenthe-stadiale Staubecken-Sedimente (Pleistozän) und ihr Lagerungsverband aus zwei Aufschlüssen im Wesertal zwischen Rinteln und Hameln. – 58 S.; unpublished diploma thesis; University of Hannover.

Lambeck, K., Purcell, A., Funder, S., Kjaer, K.H., Larsen, E. & Möller, P. (2006): Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from the field data and rebound modelling. – Boreas, 35: 539–575.

LaRoque, A., Dubois, J.-M.M. & Leblon, B. (2003): A methology to reconstruct small and short-lived ice-dammed lakes in the Appalachians of Southern Québec. – Quaternary International, 99–100: 59–71.

Latzke, A. (1996): Sedimente und Internbau des Kiessandkörpers von Freden/Leine. – 76 S.; unpublished diploma thesis; University of Hannover.

Liedtke, H. (1981): Die nordische Vereisung in Mitteleuropa. – Forschung zur deutschen Landeskunde, 204: 1–307.

Liszkowski, J. (1993): The effects of Pleistocene ice-sheet loading/deloading cycles on the bedrock structure of Poland. – Folia Quaternaria, 64: 7–23.

Litt, T., Behre, K.-E., Meyer, K.-D., Stephan, H.-J. & Wansa, S. (2007): Stratigraphische Begriffe für das Quartär des nordeutschen Vereisungsgebietes. – Eiszeitalter und Gegenwart, 56: 7–65.

Lønne, I. (1995): Sedimentary facies and depositional architecture of ice-contact glaciomarine systems. – Sedimentary Geology, 98: 13–43.

Lønne, I. (2001): Dynamics of marine glacier termini read from moraine architecture. – Geology, 29: 199–202.

Lüttig. G. (1954): Alt- und mittel-pleistozäne Eisrandlagen zwischen Harz und Weser. – Geologisches Jahrbuch, 70: 43–125.

Lüttig. G. (1958): Heisterbergphase und Vollgliederung des Drenthe-Stadiums. – Geologisches Jahrbuch, 75: 419–430.

Lüttig. G. (1960): Neue Ergebnisse quartärgeschichtlicher Forschung im Raum Alfeld-Hameln-Elze. Geologisches Jahrbuch, 77: 337–390.

Lüttig. G. (1962): Das Braunkohlebecken von Bornhausen am Harz. – Geologisches Jahrbuch, 79: 565–662.

Meinsen, J., Winsemann, J., Weitkamp, A., Landmeyer, N., Lenz, A. & Dölling, M. (in press): Middle Pleistocene (Saalian) lake outburst floods in the Münsterland Embayment (NW Germany): impacts and magnitudes. – Quaternary Science Reviews.

Merkt, J. (1978): Zur Bildung der Quellmoore bei Todenmann/Wesergebirge: Die geologischen Voraussetzungen. Geologisches Gutachten über die Ursachen der Bildung von Quellmooren bei Todenmann/Wesergebirge. – Arbeitsstudie für theoretische und angewandte Pflanzensoziologie, 1–3.

Meyer, T. (2003): Faziesarchitektur glazilakustriner Eiskontakt-Fächer in Südniedersachsen. – 230 S.; unpublished diploma thesis; University of Hannover.

Miotke, F.-D. (1971): Die Landschaft an der Porta Westfalica. Teil 1: Die Naturlandschaft. – Jahrbuch der Geographischen Gesellschaft Hannover 1969: 1–256.

Moretti, I., Calassou, S., Victor, P., Molinaro, M. & Maerten, L. (2003): Syn-sedimentary shear zones. – Petroleum Geoscience, 9: 221–232.

Mulder, T. & Alexander, J. (2001): The physical character of subaqueous sedimentary density flows and their deposits. – Sedimentology, 48: 269–299.

Müller, G. (1896): Glaziale Ablagerungen im südlichen Hannover und am nördlichen Harzrande. – Zeitschrift der deutschen Geologischen Gesellschaft, 48: 431–434.

Naumann, E. (1922): Erläuterungen zu Blatt 3820 Rinteln, Geologische Karte von Preußen 1: 25 000. – 46 S.; Berlin.

Naumann, E. (1927): Erläuterungen zu Blatt 3823 Eldagsen, Geologische Karte von Preußen 1: 25 000. – 57 S.; Berlin.

Naumann, E. & Burre O. (1927): Erläuterungen zu Blatt 3822 Hameln, Geologische Karte von Preußen 1: 25 000. – 77 S.; Berlin.

Nemec, W. (1990): Aspects of sediment movement on steep delta slopes. – In: Colella, A. & Prior, B.D. (eds.): Coarse-Grained Deltas. – IAS Specical Publications, 10: 29–73.

Nemec, W., Lønne, I. & Blikra, L.H. (1999): The Kregnes moraine in Gaudalen, west-central Norway: Anatomy of a Younger Dryas proglacial delta in a paleofjord basin. – Boreas, 28: 454–476.

Passchier, S., Laban, C., Mesdag, C.S. & Rijsdijk, K.F. (2010): Subglacial bed conditions during Late Pleistocene glacitaions and their impact on ice dynamics in the southern North Sea. – Boreas, 39: 633–647.

Petter, A.L. & Muto, T. (2008): Sustained alluvial aggradation and autogenic detachment of the alluvial river from the shoreline in response to steady fall of relative sea-level. – Journal of Sedimentary Research, 78: 98–111.

Plink-Björklund, P. & Ronnert, L. (1999): Depositional processes and internal architecture of late Weichselian ice-margin submarine fan and delta settings, Swedish west coast. – Sedimentology, 46: 215–234.

Posamentier, H.W. Allan, G.P. & James, D.P. (1992): High-resolution sequence stratigraphy – the east Coulee delta, Alberta. – Journal of Sedimentary Petrology, 62: 310–317.

Postma, G. & Cruickshank, C. (1988): Sedimentology of a late Weichselian to Holocene terraced fan delta, Varangerfjord, northern Norway. – In: Nemec, W. & Steel, R.J. (eds.): Fan Deltas: Sedimentology and Tectonic Settings: 144–157; London (Blackie).

Powell, R.D. (1990): Glacimarine processes at grounding-line fans and their growth to ice-contact deltas. – In: Dowdeswell, J.A. & Scourse, J.D. (eds.): Glacimarine Environments: Processes and Sediments. – Geological Society of London Special Publications, 53: 53–73.

Powell, R.D. & Domack (1995): Modern Glaciomarine Environments. – In: Menzies, J. (ed.): Modern Glacial Environments: 445 –486; Oxford (Butterworth –Heinemann).

Prange, W. (1995): Kleintektonische Untersuchungen in Lockersedimenten. – Schriften des Naturwissenschaftlichen Vereins Schleswig-Holsteins, 65: 47–65.

Rakowski, B. (1990): Aufbau und Genese der „Emme“ – eines Schmelzwasser-Schwemmfächers an der Südseite des Wesergebirges bei Kleinenbremen (Bückeburg). – 95 S.; unpublished diploma thesis; University of Hannover.

Rausch, M. (1975): Der „Dropstein-Laminit“ von Bögerhof und seine Zuordnung zu den Drenthe-zeitlichen Ablagerungen des Wesertals bei Rinteln. – Mitteilungen aus dem Geologischen Institut der Universität Hannover, 12: 51–84.

Rausch, M. (1977): Fluß-, Schmelzwasser- und Solifluktionsablagerungen im Terrassengebiet der Leine und der Innerste. – Mitteilungen aus dem Geologischen Institut der Universität Hannover, 14: 1–82.

Reicherter, K., Kaiser, A. & Stackebrandt, W. (2005): The post-glacial landscape evolution of the North German Basin: morphology, neotectonics and crustal deformation. – International Journal of Earth Sciences, 94: 1083–1093.

Ritchie, B.D., Gawthorpe, R.L. & Hardy, S. (2004a): Three-dimensional numerical modelling of deltaic depositional sequences 1: influence of the rate and magnitude of sea-level change. – Journal of Sedimentary Research, 74: 203–220.

Ritchie, B.D., Gawthorpe, R.L. & Hardy, S. (2004b): Three-dimensional numerical modelling of deltaic depositional sequences 2: influence of local controls. – Journal of Sedimentary Research, 74: 221–238.

Rohde, P. & Thiem, W. (1998): Die eiszeitliche Weser im heutigen Weser- und Leinetal. – In: Feldmann, L. & Meyer, K.D. (eds.): Quartär in Niedersachsen. Exkursionsführer zur Jubiläums-Hauptversammlung der Deutschen Quartärvereinigung in Hannover, Exkursion C: 89–153.

Röhm, H. (1985): Bau und Zusammensetzung Saale-Eiszeitlicher Sedimentkörper im Raum Hausberge-Veltheim/Weser. – 107 S.; unpublished diploma thesis; University of Hannover.

Russell, H.A.J. & Arnott, R.W.C. (2003): Hydraulic-jump and hyperconcentrated-flow deposits of a glacigenic subaqueous fan: Oak Ridge Moraine, southern Ontario, Canada. – Journal of Sedimentary Research, 73: 887–905.

Russell, H.A.J., Sharpe, D.R. & Bajc, A.F. (2007): Sedimentary signatures of the Waterloo Moraine, Ontario, Canada. – In: Hambrey, M., Christoffersen, P., Glasser N & Hubbard, B. (eds.): Glacial Processes and Products. – IAS Specical Publications, 39: 85–108.

Schumm, S.A. (1993): River response to base level change: implications for sequence stratigrahy. – Journal of Geology, 101: 279–294.

Schwarzbach, M. (1950): Kamebildungen im Leinetal (Hannover). – Neues Jahrbuch für Geologie und Paläontologie Monatshefte: 328–329.

Selsing, L. (1981): Stress analysis on conjugate normal faults in unconsolidated Weichselian glacial sediments from Brorfelde, Denmark. – Boreas, 10: 275–279.

Seraphim, E. T. (1973): Eine saalezeitliche Mittelmoräne zwischen Teutoburger Wald und Wiehengebirge. – Eiszeitalter und Gegenwart, 23/24: 116–129.

Seraphim, E. T. (1972): Wege und Halte des saalezeitlichen Inlandeises zwischen Osning und Weser. – Geologisches Jahrbuch, Reihe A, 3: 1–85.

Sharpe, D. R. (1988): Glaciomarine fan deposits in the Champlain Sea. In: Gadd, N.R. (ed.): The Late Quaternary Development of the Champlain Sea Basin. – Canadian Geological Association Special Paper, 35: 63–82.

Sharpe, D. R. & Cowan, W.R. (1990): Moraine formation in northwestern Ontario: product of subglacial fluvial and glacilacustrine sedimentation. – Canadian Journal of Earth Sciences, 27: 1478–1486.

Siegert, L. (1912) Über die Entwicklung des Wesertales. – Zeitschrift der deutschen Geologischen Gesellschaft, 64: 233–264.

Siegert, L. (1921): Beiträge zur Kenntnis des Pliozäns und der diluvialen Terrassen im Flußgebiet der Weser. – Abhandlungen der Preußischen geologischen Landes-Anstalt, Neue Folge, 90:1–130.

Sirocko, F., Szeder, T., Seelos, C., Lehné, R., Rein, B., Schneider, W.M. & Dimke, M. (2002): Young tectonic and halokinetic movements in the North-German-Basin: its effect on formation of modern rivers and subsurface morphology. – Netherlands Journal of Geosciences / Geologie en Mijnbouw, 81: 431–441.

Sirocko, F., Reicherter, K., Lehné, R., Hübscher, C., Winsemann, J. & Stackebrandt, W. (2008): Glaciation, salt and the present landscape. – In: Littke, R., Bayer, U., Gajewski, D. & Nelskamp, S. (eds): Dynamics of Complex Intracontinental Basins – The Central European Basin System: 232–245, Berlin (Springer).

Skupin, K., Speetzen, E. & Zandstra, J.G. (1993): Die Eiszeit in Nordwestdeutschland. Zur Vereisung der Westfälischen Bucht und angrenzender Gebiete. – 95 S.; Krefeld (Geologisches Landesamt Nordrhein-Westfalen).

Skupin, K., Speetzen, E. & Zandstra, J. G. (2003): Die Eiszeit in Nordost-Westfalen und angrenzenden Gebieten Niedersachsens. – 96 S.; Krefeld (Geologischer Dienst Nordrhein-Westfalen).

Soergel, W. (1921): Die Ursachen der diluvialen Aufschotterung und Erosion. – Zeitschrift der deutschen Geologischen Gesellschaft, 64: 233–264.

Sohn, Y.K. (2000): Depositional processes of submarine debris flows in the Miocene fan deltas, Pohang basin, SE Korea with special reference to flow transformation. – Journal of Sedimentary Research, 70: 491–503.

Sohn, Y.K., Kim, S.B., Hwang, I.G., Bahk, J.J., Choe, M.Y., & Chough, S.K. (1997): Characteristics and depositional processes of large-scale gravelly Gilbert-type foresets in the Miocene Dousan fan delta, Pohang Basin, SE Korea. – Journal of Sedimentary Research, 67: 30–141.

Sohn, Y.K., Choe, M.Y. & Jo, H.R. (2002): Transition from debris flow to hyperconcentrated flow in a submarine channel (the Cretaceous Cerro Toro Formation, southern Chile). – Terra Nova 14: 405–415.

Spethmann, H. (1908): Glaziale Stillstandslagen im Gebiet der mittleren Weser. – Mitteilungen der Geographischen Gesellschaft Lübeck, 22: 1–17.

Stach, E. (1930): Die Eisrandbildungen an der Porta Westfalica. – Jahrbuch der Preussischen Geologischen Landes-Anstalt, 51: 174–187.

Stewart, I.S., Sauber, J. & Rose, J. (2000): Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. – Quaternary Science Reviews, 19: 1367–1389.

Stokes, C.R. & Clark, C.D. (2004): Evolution of late glacial ice-marginal lakes on the northwestern Canadian Shield and their influence on the location of the Dubawnt Lake palaeo-ice stream. – Palaeogeography, Palaeoclimatology, Palaeoecology, 215: 155–171.

Struck, R. (1904): Der baltische Höhenrücken in Holstein. – Mitteilungen der Geographischen Gesellschaft und naturkundliches Museum Lübeck, 19: 1–103.

Teller, J.T. (1995): History and drainage of large ice-dammed lakes along the Laurentide Ice Sheet. – Ouaternary International, 28: 83–92.

Thiem, W. (1972): Geomorphologie des westlichen Harzrandes und seiner Fußregion. – Jahrbuch der Geographischen Gesellschaft Hannover, Sonderheft 6: 1–271.

Thiem, W. (1988): Das Oberwesertal im Raum Polle-Bodenwerder-Hehlen. Zu aktuellen Problemen der Talgeschichte der Oberweser im Quartär. – Jahrbuch der Geographischen Gesellschaft Hannover, 14: 273–326.

Thomas, R.H. (1979): Ice shelves: a review. – Journal of Glaciology, 24: 273–286.

Thome, K.N. (1983): Gletschererosion und -akkumulation im Münsterland und angrenzenden Gebieten. – Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 166: 116–138.

Thome, K.N. (1998): Einführung in das Quartär: das Zeitalter der Gletscher. – 309 S. Berlin (Springer).

Uebersohn, D. (1990): Aufbau und Alter pleistozäner Lockersedimente bei Bornhausen (nordwestliches Harzvorland). – 57 S.; unpublished diploma thesis; University of Hannover.

Van den Berg, M.W. & Beets, D.J. (1987): Saalian glacial deposits and morphology in The Netherlands. – In: Van der Meer, J.J.M. (ed): Tills and Glaciotectonics, 235–251; Rotterdam (Balkema).

Vollbrecht, A. & Tanner, D.C. (in press): Der Leinetalgraben als Teil einer regionalen Pull-Apart-Struktur. – In: Leiss, B., Tanner, D. & Vollbrecht, A. (eds.): Neuere Untersuchungen zur Geologie der Leinetalgrabenstruktur – Bausteine zur Erkundung des geothermischen Nutzungspotentials in der Region Göttingen. – Universitätsdruck Göttingen.

Waldeck, H. (1975): Erläuterungen zu Blatt 4023 Eschershausen, Geologische Karte von Niedersachsen 1: 25 000. – 189 S.; Hannover.

Wahle, M., Brandes, C, Polom, U. & Winsemann, J. (2010): Evolution of Middle Pleistocene glacial Lake Leine (NW Germany): challenges on

the way to reconstruct lake-level history and palaeogeography. – Abstract volume, S. 173; Deuqua Meeting 2010, Greifswald.
Warren, C.R., Greene, D.R. & Glasser, N.F. (1995): Glaciar Upsala, Patagonia: Rapid calving retreat in fresh water. – Annals of Glaciology, 21: 311–316.
Wellmann, P. (1998): Kies-/Sandkörper im Wesertal zwischen Rinteln und Porta Westfalica. – Mitteilungen aus dem Geologischen Institut der Universität Hannover, 38: 203–212.
Wermbter, H. (1891): Der Gebirgsbau des Leinetals zwischen Greene und Banteln. – Neues Jahrbuch für Mineralogie, Geologie und Paläontologie, Beilagen-Band, 7: 386–398.
Winsborrow, M.C.M., Clarke, C.D. & Stokes, C.R. (2010): What controls the location of ice streams? – Earth-Science Reviews, 103: 45–59
Winsemann, J., Asprion, U., Meyer, T., Schultz, H., & Victor P. (2003): Evidence of iceberg ploughing in a subaqueous ice-contact fan, glacial Lake Rinteln, Northwest Germany. – Boreas, 32: 386–398.
Winsemann, J., Asprion, U. & Meyer, T. (2004): Sequence analysis of early Saalian glacial lake deposits (NW Germany): evidence of rapid local ice margin retreat and related calving processes. – Sedimentary Geology, 165: 223–251.
Winsemann, J., Asprion, U. & Meyer, T. (2007): Lake-level control on ice-margin subaqueous fans, glacial Lake Rinteln. – In: Hambrey, M., Christoffersen, P., Glasser N & Hubbard, B. (eds.): Glacial Processes and Products. – IAS Specical Publications, 39: 121–148.
Winsemann, J., Asprion, U., Meyer, T. & Schramm, C. (2007): Facies characteristics of Middle Pleistocene (Saalian) ice-margin subaqueous fan and delta deposits, glacial Lake Leine, NW Germany. – Sedimentary Geology, 193: 105–129.
Winsemann, J., Hornung, J.J., Meinsen. J., Asprion, U., Meinsen, Polom, Brandes, C. Bussmann, M & Weber, C. (2009): Anatomy of a subaqueous ice-contact fan and delta complex, Middle Pleistocene, NW Germany. – Sedimentology, 56: 1041–1076.
Winsemann, J., Brandes, C. & Polom, U. (2011): Response of a proglacial delta to rapid high-amplitude lake level change: an integration of outcrop data and high resolution shear wave seismic. – Basin Research, 23: 22–52. Doi: 10.1111/j.1365 –2117.2010.00468.x.
Wortmann, H. (1968): Die morphogenetische Gliederung der Quartärbasis des Wiehengebirgsvorlandes in Nordwestdeutschland. – Eiszeitalter und Gegenwart 19: 227–239.
Wortmann, H., Wortmann, A. (1987): Glaziäre Ablagerungen und Terrassengliederung der Weser im Raum zwischen Eisbergen und Porta Westfalica (Nordwestdeutschland). – Eiszeitalter und Gegenwart 37: 93–98.

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Chronology of Weichselian main ice marginal positions in north-eastern Germany

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Abstract: The chronology of the Weichselian Pleniglacial in north-eastern Germany was so far mainly based on morphostratigraphy and radiocarbon ages of organic sediments underlying glacigenic deposits. Throughout the last years direct dating approaches, i.e. Optically Stimulated Luminescence (OSL) dating of glacioflucial deposits and surface exposure dating (SED) of erratic boulders, have been applied in a number of studies. We summarise and reassess the results of these studies following a process based interpretation model and propose a new chronology for the main ice marginal positions in north-eastern Germany. The available data give evidence for a twofold last glaciation with the Brandenburg phase representing an ice advance which occurred in late Marine Isotope Stage (MIS) 3 to early MIS 2, and the Pomeranian phase representing an ice advance reaching its maximum extent at ~20 ka. The final stabilisation of the land surface after initial deglaciation was highly dependent on active landscape transformation during phases characterised by periglacial conditions. First numerical ages point towards the occurrence of such an activity phase at about ~15 ka.

[Chronologie weichselzeitlicher Haupteisrandlagen in Nord-Ost-Deutschland]

Kurzfassung: Bisher basierte die Chronologie des Weichsel-Pleniglazials in Nord-Ost-Deutschland im Wesentlichen auf morphostratigraphischen Befunden und Radiokohlenstoffdatierungen organischer Sedimente aus dem Liegenden glazigener Ablagerungen. Im Laufe der letzen Jahre kamen im Rahmen verschiedener Studien Datierungsmethoden zum Einsatz, mit deren Hilfe es möglich war, die glazigenen Sedimente direkt zu datieren: Optisch Stimulierte Lumineszenz (OSL) von glazifluvialen Sedimenten und Oberflächen-Expositionsdatierungen (surface exposure dating, SED) von erratischen Blöcken. Wir fassen die Ergebnisse dieser Studien zusammen und bewerten sie auf der Grundlage eines prozessbasierten Interpretationsschemas neu, um somit eine neue Chronologie für die weichselzeitlichen Haupteisrandlagen in Nord-Ost-Deutschland vorstellen zu können. Auf der Grundlage der verfügbaren Daten lassen sich zwei Phasen während des letzten Glazials nachweisen, wobei die Brandenburger Phase einen Eisvorstoß im späten Marinen Isotopenstadium (MIS) 3 bis frühen MIS 2 repräsentiert, während die Pommersche Phase einen Eisvorstoß widerspiegelt, der seinen Maximalstand um ~20 ka erreichte. Hinsichtlich der endgültigen Stabilisierung der Geländeoberflächen nach der initialen Eisfreiwerdung zeigt sich eine hohe Abhängigkeit von Phasen aktiver Transformation unter periglazialen Bedingungen. Erste Ergebnisse numerischer Datierungen deuten auf eine solche Aktivitätsphase um ~15 ka hin.

Keywords: *Weichselian glaciation, Optically Stimulated Luminescence, OSL, surface exposure dating, Pomeranian Phase, Frankfurt Phase, Brandenburg Phase, deglaciation*

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1 Introduction

North-eastern Germany is an area with a long tradition of Quaternary research and was the type area where the glacial theory was established for Northern Germany by the end of the 19th century (summarised in Lüthgens & Böse 2010). In contrast to adjacent areas such as the Jutland Peninsula and parts of Mecklenburg-Vorpommern, the ice marginal positions of the Weichselian Glaciation especially in Brandenburg are located well to the north of the maximum extent of previous glaciations (Fig. 1) and well apart from each other (Fig. 2). Hence, this area is particularly suitable for geochronometrical studies, because the assignment of glacial landforms to a specific ice advance is mainly straightforward. However, during the past 130 years the classification of the Weichselian Pleniglacial has mainly been based on morphostratigraphical interpretations. As Terberger et al. (2004) pointed out, a reliable chronology of the Weichselian ice decay based on numerical ages is still lacking. Assumed ages of ice marginal positions are either pure estimates or are based on extrapolations of radiocarbon ages from covering or underlying organic sediments. However, during the last years a significant number of studies using different numerical dating techniques have been conducted in north-eastern Germany. The aim of this review is to integrate the individual results of these studies into a coherent model for the Weichselian landscape development and to discuss this model in the context of results from neighbouring countries such as Poland and Denmark.

2 Morphostratigraphy

Based on the conceptual model of the glacial series (sequence of typical geomorphological units formed at a stationary ice margin, Penck 1882), first syntheses of the glacial landscape in the peribaltic were provided by, for example, Keilhack (1909). Already in the early 20th century Woldstedt (1925) introduced the pattern of ice marginal

Fig. 1: Maximum extents (from south to north) of the Elsterian (dark blue), Saalian (blue) and Weichselian (light blue) glaciations in Germany and neighbouring areas (data provided by Ehlers & Gibbard 2004). Figure based on a digital elevation model (DEM) derived from hole-filled seamless SRTM data (processed by Jarvis et al. 2006). (Figure modified from Lüthgens 2011).

Abb. 1: Maximalausdehnungen (von Süd nach Nord) des Elster-Glazials (dunkelblau), Saale-Glazials (blau) und des Weichsel-Glazials (hellblau) in Deutschland und benachbarten Gebieten (Daten bereitgestellt von Ehlers & Gibbard 2004). Abbildung basiert auf einem digitalen Höhenmodell (DHM) abgeleitet aus SRTM Daten (prozessiert von Jarvis et al. 2006). (Abbildung verändert nach Lüthgens 2011).

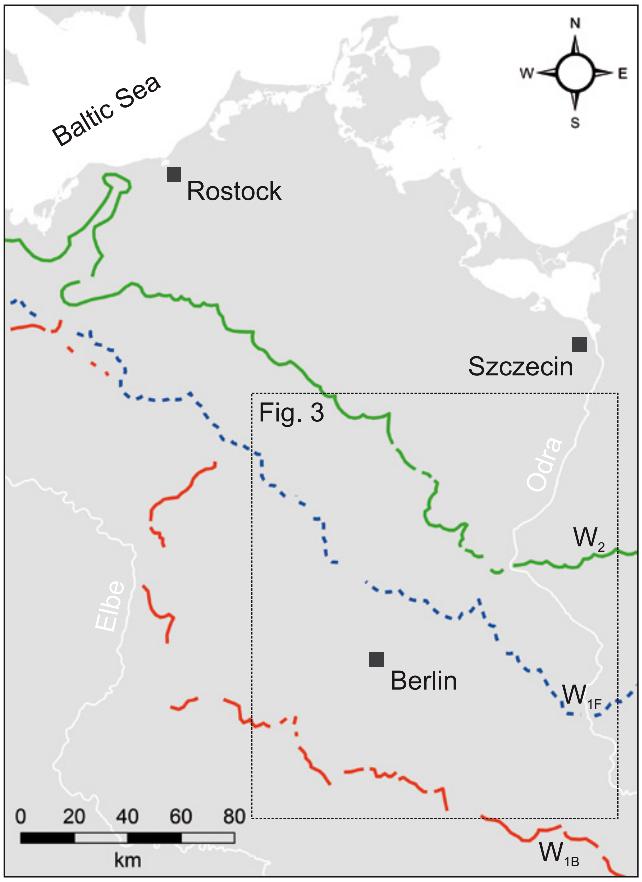

Fig. 2: North-eastern Germany and neighbouring areas of Denmark and Poland, selected cities, and major rivers. Main Weichselian ice marginal positions according to Liedtke (1981): W_{1B} – Brandenburg phase (red line), W_{1F} – Frankfurt recessional phase (dashed blue line), W_2 – Pomeranian phase (green line). (Figure modified from Lüthgens 2011).

Abb. 2. Nord-Ost-Deutschland und benachbarte Gebiete von Dänemark und Polen, ausgewählte Städte und Haupt-Fließgewässer. Weichselzeitliche Haupteisrandlagen nach Liedtke (1981): W_{1B} – Brandenburger Phase (rote Linie), W_{1F} – Frankfurter Rückzugs-Phase (gestrichelte blaue Linie), W_2 – Pommersche Phase (grüne Linie). (Abbildung verändert nach Lüthgens 2011).

positions (IMPs) which in general is still valid today. He assigned landforms south of the Glogów-Baruth ice marginal valley (IMV) to the penultimate glaciation and differentiated two phases for the formation of main ice marginal positions during the last glaciation. The “Jütische Phase” consists of the “Brandenburger Phase” and the “Posensche Subphase”. The “Pommersche Phase” follows to the north. This morphostratigraphical model already implied a first relative chronology with the southernmost IMP representing the oldest ice advance and a succession of younger IMPs northward towards the Baltic Sea basin (summarised in Lüthgens 2011). Apart from these three main IMPs a complex pattern of intermediary systems of recessional terminal moraines has been controversially discussed within scientific discourse (summarised in Böse 1994, 2005, Lüthgens & Böse 2010). Despite such conflicting interpretations on regional and local scales, the general pattern established by Woldstedt (1925) was later confirmed by Liedtke (1975) who differentiates three main IMPs (Fig. 2): the Brandenburg (W_{1B}) IMP representing the southernmost extent of the Weichselian glaciation, the Frankfurt IMP (W_{1F}) and the Pomeranian IMP (W_2). Although specific IMVs (“Urstromtäler”) have frequently been assigned to these main IMPs (Glogów-Baruth IMV & Brandenburg IMP, Warszawa-Berlin IMV & Frankfurt IMP, Toruń-Eberswalde IMV & Pomeranian IMP), the drainage of meltwater has been shown to be highly complex (e.g., Juschus 2001), with IMVs and meltwater channels still in use after the Scandinavian Ice Sheet (SIS) had retreated north of the Pomeranian IMP. The characteristics of the main IMPs in northeastern Germany will be summarised in the following.

Brandenburg phase (W_{1B}) and Frankfurt phase (W_{1F})

Ice marginal features related to the Brandenburg phase and the Frankfurt phase are relatively weakly developed. Due to the rare occurrence of terminal moraines or even push-moraines, both IMPs have mainly been reconstructed along ridges of outwash plains (sandar). Additionally, Saalian push-morainic complexes are known to have been preserved in some places (Böse 2005). This implies an ice advance that adapted to the morphology inherited from the penultimate glaciation (Brose 1995, Brauer, Tempelhoff

& Murray 2005, Lüthgens, Böse & Krbetschek 2010). Glaciofluvial deposits and landforms as well as dead ice topography dominate the area between the Brandenburg IMP and the Pomeranian IMP which includes the Frankfurt IMP. Although minor outwash plains and kames occur, they can hardly be assigned to specific IMPs (Böse 2005). The area is furthermore characterised by intensive glaciofluvial erosion related to the development of a complex system of interconnecting meltwater channels in between the ice marginal valleys. The ice advance to the southernmost Brandenburg IMP has traditionally been ascribed to the Last Glacial Maximum (LGM). The term LGM was originally defined as the global maximum ice volume inferred from the marine isotope record at ~20 ka (Bard 1999), but it is also used as a term describing the maximum ice extent on regional scales. The Brandenburg IMP was supposed to represent the LGM according to both definitions. The Frankfurt IMP is considered to represent a halt in the course of the down-melting of stagnant or even dead ice related to the ice advance to the Brandenburg IMP (Lippstreu 1995, Böse 2005, Litt et al. 2007).

Pomeranian phase (W_2) and recessional phases

The most prominent terminal moraines in north-eastern Germany were formed during the Pomeranian phase which is often assumed to represent a strong re-advance of the SIS originating from the Baltic Sea basin (e.g. Lippstreu 1995, Böse 2005). However, other authors (e.g. Kliewe & Jahnke 1972, Liedtke 2001) argue that it is more likely that the SIS ice margin remained south of the Baltic Sea basin, because there is no evidence for an interstadial between the $W_{1B/F}$ and the W_2 phases. Ice marginal features north of the Pomeranian IMP (the most prominent ascribed to the Mecklenburg phase, forming the terminal moraines of the Rosenthal and Velgast IMPs) document the retreat of the SIS further north towards the end of the Weichselian glaciation (Böse 2005).

3 Radiocarbon based chronology

With the introduction of radiocarbon dating (Libby 1952), the morphostratigraphically based relative chronology was assigned with actual ages (e.g. Cepek 1965, Liedtke 1996, Kozarski 1995, Marks 2002, see Table 1). The German Stratigraphic Commision (Litt et al. 2007 and available from the lithostratigraphic lexicon Litholex http://www.bgr.bund.de/litholex which also incorporates more recent data) and Lüthgens (2011) recently reviewed the available geochronometrical data (Table 1). However, this radiocarbon based chronology suffers from a number of significant drawbacks. Radiocarbon dating can only be applied to organic deposits. These are usually found in positions under- or overlying minerogenic glacigenic deposits, therefore the obtained ages only provide maximum or minimum ages for the latter. Additional problems may arise whenever the dated organic material is not found to be in situ, but has been reworked by, for example, glacial processes. The ages stated as estimates in Table 1 are mainly based on the model of ice build-up and decay developed by Kozarski (1992, 1995). Based on results from radiocarbon dating from organic deposits underlying the Weichselian glacigenic deposits, he estimated average rates of ice build-up and decay of the SIS over time and hereby calculated ages for the different IMPs. Given these different uncertainties the validity of the radiocarbon based chronology has to be regarded as being very limited.

*Tab. 1: ^{14}C based chronology of the main IMPs in north-eastern Germany**

Tab. 1: ^{14}C basierte Chronologie der Haupteisrandlagen in Nord-Ost-Deutschland

IMP	Age**	Method
Brandenburg (W_{1B})	~20 ka BP	Estimate[1]
	<24 cal. ka BP	^{14}C[2]
Frankfurt (W_{1F})	~18.8 ka BP	Estimate[3]
	<23.8 cal. ka BP	^{14}C[4]
	<32 cal. ka BP	^{14}C[5]
Pomeranian (W_2)	~16.2 ka BP	Estimate[6]
	<17.6 cal. ka BP	^{14}C[7]

1 Cepek (1965), Liedtke (1981), Kozarski (1995)
2 Age of organic sediments underlying glacial sediments of the Brandenburg phase (Marks 2002).
3 Age extrapolated from underlying ^{14}C ages, assuming an estimated rate of ice build-up and decay Kozarski (1995).
4 Age of organic sediments underlying glacial sediments of the Poznan (Frankfurt) phase near Konin, Poland (Marks 2002).
5 Age of an organic silt layer ("Mudde vom Segrahner Berg") underlying glacial sediments of the Frankfurt phase (Lüttig 2005).
6 Age extrapolated from underlying ^{14}C ages, assuming an estimated rate of ice build-up and decay Kozarski (1995).
7 Age of organic sediments (Liedtke 1996, Marks 2002), origin and stratigraphical position unclear from primary sources.

* Summarised from Litt et al. (2007), no age uncertainties specified.
** Calibration of ^{14}C ages according to Stuiver et al. (1998) by Litt et al. (2007).

4 Direct dating of glacigenic deposits

With the advancements of numerical dating techniques two approaches to directly date glacigenic deposits are now available: Optically Stimulated Luminescence (OSL) dating of glaciofluvial sediments and surface exposure dating (SED) of glacigenic boulders using cosmogenic nuclides (most commonly ^{10}Be).

OSL dating techniques rely on quartz and feldspar that store radiation damage caused by ionising radiation within their crystal lattice as a latent signal (Bøtter-Jensen et al. 2003) as long as the minerals are sealed from daylight. Once the minerals are exposed to daylight (e.g. during sediment transport) the OSL signal is reset to zero. The latent OSL signal accumulated during deposition can be measured in the laboratory. The intensity of the signal is a measure for the amount of energy stored within the crystal (equivalent dose) (Bøtter-Jensen et al. 2003; Preusser et al., 2008). Once the rate of stored energy per time is known (dose rate), it is possible to calculate the time elapsed since the crystal was last exposed to daylight. Therefore OSL enables the determination of depositional ages of sediments. However, the proglacial depositional environment is characterised by cloudy meltwater, high sedimentation rates and short transport distances. This may cause insufficient exposure of the mineral grains to daylight and consequently the incomplete resetting of the OSL signal prior to deposition. Different approaches are available in order to deal with this problem. Most commonly used is the analysis of equivalent dose (D_e) distributions using statistical minimum age models. The D_e is determined by comparing the natural luminescence signal with that of laboratory irradiated subsamples (aliquots). Nowadays the single aliquot regenerative (SAR) dose protocol (Murray & Wintle 2000, 2003, Wintle & Murray 2006) is most commonly used in luminescence dating laboratories worldwide. Here all measurement steps necessary for D_e determination are conducted using the same aliquot. By measuring several aliquots for a single OSL sample, D_e datasets are generated which are suitable for statistical analyses such as the aforementioned statistical age models (e.g. Galbraith et al. 1999, Bailey & Arnold 2006, Fuchs & Owen 2008, Thrasher et al. 2009). A second approach in order to deal with incompletely bleached samples is the reduction of the number of grains per measured subsample (aliquot) ideally down to the single grain level as suggested by Duller (2008). The detectable OSL signal from multigrain aliquots is always an averaged signal consisting of OSL signals emitted by individual grains. By measuring single grains, this averaging effect can be avoided and fractions of well bleached and incompletely bleached grains within heterogeneously bleached samples can be separated. If incomplete bleaching sometimes can not be overcome (e.g. if single grain measurements are not possible due to the luminescence properties of mineral grains within a sample) the obtained ages have to be regarded as maximum ages. For further details on the basic principles and latest developments in OSL dating we refer to recently published methodological review papers (Lian & Roberts 2006, Preusser et al. 2008, Wintle 2008a/b).

Surface exposure dating is based on the principle that cosmogenic nuclides build up in minerals exposed to cosmic rays at a predictable rate over time. By measuring the nuclide concentration in samples taken from e.g. rock surfaces or boulders, it is possible to determine how long the sampled material has been exposed at the surface (Ivy-Ochs & Kober 2008). Using mass spectrometric techniques, a broad variety of cosmogenic nuclides can be measured (Gosse & Phillips 2001). Most commonly used are the radionuclides ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl. For a comprehensive review of the theoretical background and the application of cosmogenic nuclide methods we refer to Gosse & Phillips (2001). A review focussing on the dating of landforms and deposits by means of SED is available from Ivy-Ochs & Kober (2008). Within the two studies providing SED ages for north-eastern Germany to be introduced in the following, different calculation scenarios with respect to different scaling methods and/or correction factors for snow cover, vegetation cover and erosion were provided. Additionally, Rinterkecht et al. (2010) recalculated the SED ages of Heine et al. (2009) for samples from the Pomeranian phase. For reasons of comparability we will only provide uncorrected SED ages calculated according to the Lal (1991)/Stone (2000) (Lm) scaling scheme as calculated by Rinterknecht et al. (2010). On the one hand the Lm scaling scheme is assumed to be more appropriate for the age range than alternative scaling themes (Rinterknecht et al. 2010), on the other hand, the correction factors for snow, vegetation and erosion introduce additional sources of uncertainty as they are estimates. The three ages for boulders associated with the Brandenburg phase from Heine et al. (2009) had to be recalculated accordingly for this review paper using the CRONUS-Earth online ^{10}Be exposure age calculator version 2.2 (http://hess.ess.washington.edu/math) (Balco et al. 2008). However, it needs to be stressed that all the different calculation scenarios including the new calculations for this review yield ages which agree within error for the individual samples.

It has to be pointed out that OSL and SED date different processes within the development of glacial landscapes. When OSL is applied to glaciofluvial sands of outwash plains, the process of sediment aggradation linked to meltwater discharge from an ice margin is directly dated. SED applied to erratics determines the age of the exposure and final stabilisation of the sampled boulder after the downmelting of stagnant ice, landscape transformation under periglacial conditions, and the melting of buried dead ice (secondary deglaciation sensu Everest & Bradwell 2003). This is likely to cause a significant time lag between the initial deglaciation (process intended to be dated) and the final stabilisation and exposure of boulders at the landscape surface (process actually dated). Following Lüthgens & Böse (2010) and Lüthgens, Böse & Preusser (2011), we therefore propose to interpret SED ages as markers for phases of landscape stabilisation with the oldest exposure ages representing minimum ages of the glacigenic formation of terminal moraines at ice marginal positions. This implies a significant time lag between the ages obtained from both dating methods (Lüthgens 2011). However, Lüthgens & Böse (2010) point out that the combination of both methods – given that the ages are interpreted as described above – may allow a more detailed reconstruction of regional deglaciation patterns. In contrast, the calculation of average ages needs to be handled with care because geochronological details and regional differences in landscape development may thereby be obscured (Lüthgens & Böse 2010, Lüthgens, Böse & Preusser 2011).

The application of that interpretation model also offers an explanation for the phenomenon that SED based ages for specific ice marginal positions mostly yield younger ages than expected from previous chronologies (e.g. Heine et al. 2009, Houmark-Nielsen, Björck & Wohlfarth 2006, Rinterknecht et al. 2005, 2006a/b, 2007, 2008, 2010). As described above, radiocarbon chronologies based on ages derived from organic sediments underlying glacigenic sediments can only provide maximum ages for the latter. As a result a minimum SED age must be younger than a respective maximum radiocarbon age.

5 Results of numerical dating of glacigenic deposits

According to the morphostratigraphical classification outlined above, we will firstly provide the results from the area ascribed to the Brandenburg (W_{1B}) and Frankfurt (W_{1F}) phases and secondly those from the area ascribed to the Pomeranian (W_2) and its recessional phases (in the following see Fig. 3).

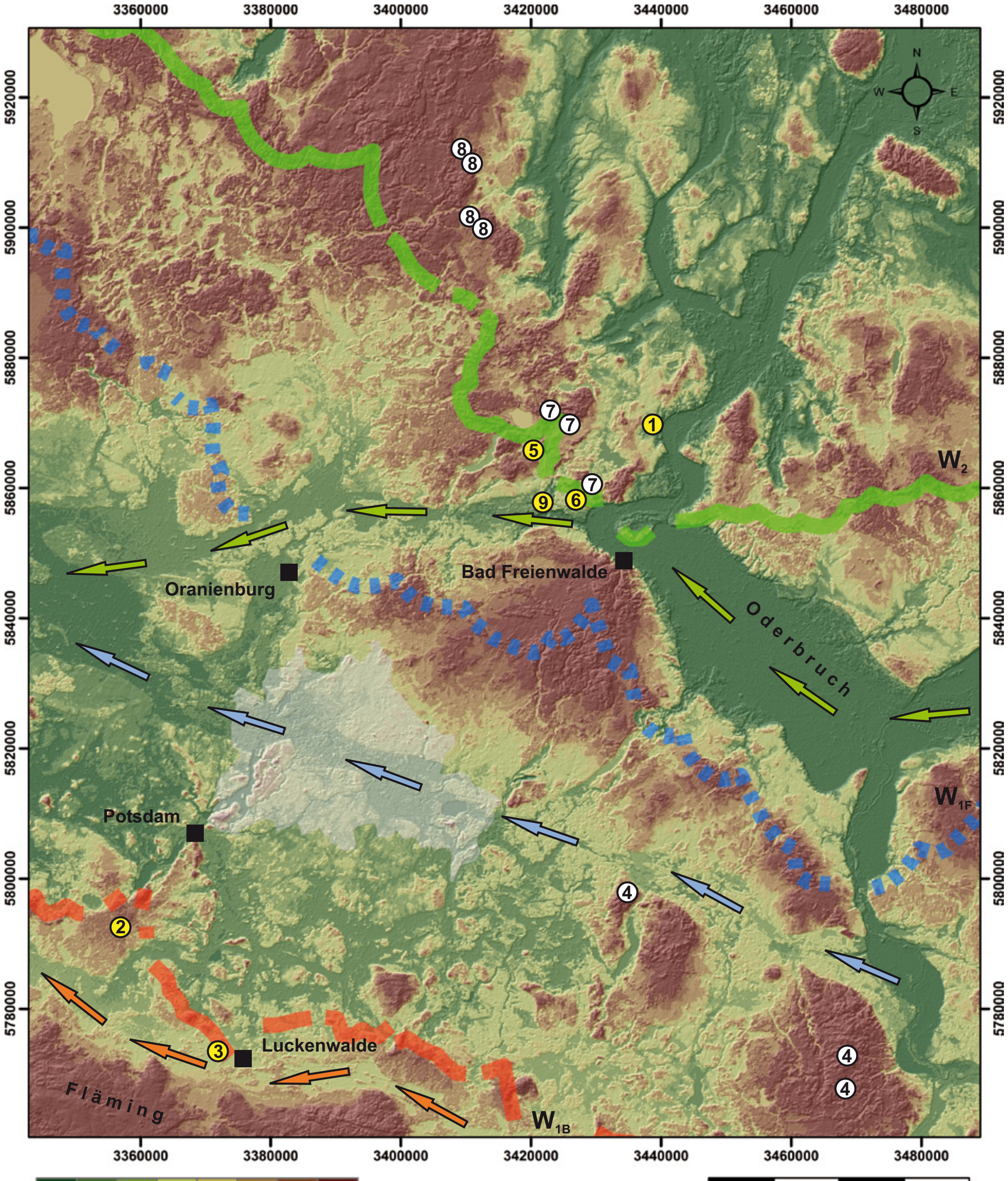

Fig. 3: Weichselian main ice marginal positions in Brandenburg, Berlin (transparent white area), and neighbouring areas according to Liedtke *(1981): W_{1B} – Brandenburg phase (orange), W_{1F} – Frankfurt recessional phase (dashed blue), W_2 – Pomeranian phase (green). Coloured arrows indicate the general course of main ice marginal valleys: Glogów-Baruth IMV (orange), Warszawa-Berlin IMV (blue), Toruń-Eberswalde IMV (green). Numbers indicate sampling locations of the studies cited in Table 2 with the background colour indicating the dating method applied (OSL – yellow, SED – white). SED locations represent the position of individual boulders sampled for a study, whereas OSL locations indicate sampling sites where multiple samples were taken. Map based on a digital elevation model (DEM) from SRTM data, 90 m resolution, UTM zone 33N, ETRS 1989.*

Abb. 3: Weichselzeitliche Haupteisrandlagen in Brandenburg, Berlin (transparent weiß unterlegter Bereich) und benachbarten Gebieten nach Liedtke *(1981): W_{1B} – Brandenburger Phase (orange), W_{1F} – Frankfurter Rückzugs-Phase (blau), W_2 – Pommersche Phase (grün). Farbige Pfeile zeigen den generellen Verlauf der Haupt-Urstromtäler an: Glogów-Baruther Urstromtal (orange), Warszawa-Berliner Urstromtal (blau), Toruń-Eberswalder Urstromtal (grün). Zahlen markieren die Beprobungsstandorte der in Tabelle 2 zitierten Studien. Die Hintergrundfarbe gibt Auskunft über die angewendete Datierungsmethode (OSL – gelb, SED – weiß). SED Markierungen entsprechen der individuellen Lage der beprobten Findlinge, OSL Markierungen dagegen entsprechen Beprobungsstandorten, an denen mehrere Proben genommen wurden. Als Kartengrundlage dient ein digitales Höhenmodell (DHM) basierend auf SRTM-Daten mit 90 m Auflösung, UTM-Zone 33N, ETRS 1989.*

5.1 Brandenburg (W_{1B}) and Frankfurt (W_{1F}) phases

For this area dating results from OSL dating of quartz as well as from SED using ^{10}Be have been published: OSL ages obtained from glaciofluvial sediments of outwash plains ascribed to the Brandenburg phase are available for the Beelitz outwash cone (Lüthgens et al. 2010, Lüthgens 2011) and the Luckenwalde area (Lüthgens, Böse & Krbetschek 2010); SED ages for three erratic boulders from the area in between the Brandenburg and Frankfurt IMPs have been published by Heine et al. (2009).

Lüthgens et al. (2010) dated three samples from glaciofluvial sediments of the Beelitz outwash cone (Fig. 3) using OSL of single aliquots of coarse grained quartz. Significant scatter in the ages determined for the individual samples was observed. The authors explain this scatter in age by the occurrence of incomplete resetting of the OSL signal prior to deposition as detected from the equivalent dose distributions obtained from the OSL measurements. Within the study a single aliquot regenerative dose protocol (SAR) was applied and multigrain aliquots were used. Therefore the authors state the youngest age of 34.1±3.0 ka obtained from the glaciofluvial sediments as a maximum age. In order to overcome the limitations in age determination caused by the incomplete resetting of the OSL signal, Lüthgens (2011) reinvestigated two of the samples from the study of Lüthgens et al. (2010) using OSL of single grains of quartz. Due to the fact that only a very small proportion (~2 %) of the measured quartz grains emitted an analysable OSL signal, the ages calculated for the samples are based on a small statistical basis. Lüthgens (2011) argues that because both samples were taken from the same stratigraphical unit (only few decimetres apart from each other) it seems plausible to calculate an average age of 27.7±4.0 ka for the two samples. This age is not significantly different from the maximum age of 34.1±3.0 ka derived from the single aliquot measurements of Lüthgens et al. (2010). In addition to these results from glaciofluvial sediments, Lüthgens et al. (2010) also dated three samples from periglacial cover sands on the Beelitz outwash cone which yielded consistent ages of ~15 ka.

Near the town of Luckenwalde (Fig. 3) Lüthgens, Böse & Krbetschek (2010) took 10 samples for coarse grain quartz OSL dating from sandur sediments exposed within two gravel pits. Although different authors had concurrently ascribed the formation of the Luckenwalde end moraine and outwash plain to the Brandenburg phase of the Weichselian glaciation, Lüthgens, Böse & Krbetschek (2010) provide evidence for a pre-Weichselian formation of the landform: seven samples from the gravel pit "Weinberge" in the southern part of the outwash plain yielded consistent ages in the range from ~130–150 ka (MIS 6). Three samples taken from glaciofluvial sediments in the northern part of the landform revealed Weichselian ages. However, due to incomplete resetting of the OSL signal Lüthgens, Böse & Krbetschek (2010b) only state a maximum age of 34.4±7.0 ka. Based on the OSL ages, results from fine gravel analyses, and mapping of deformation structures within the glaciofluvial sediments, the authors conclude that the Luckenwalde end moraine and outwash plain was initially formed during the Saalian glaciation, with the Weichselian SIS of the Brandenburg phase reaching the same position, but only reshaping parts of it primarily due to meltwater related processes.

Heine et al. (2009) sampled three boulders from the area in between the IMPs of the Brandenburg and the Frankfurt phase for SED using cosmogenic ^{10}Be (Fig. 3). The ages range from 18.9±0.9 ka for the youngest sample to 21.5±1.1 ka for the oldest sample (ages recalculated as described above). From these ages the authors deduce that the SIS reached its maximum extent during the Weichselian glaciation at 21–20 ka and started to melt back from the Brandenburg IMP at around 19 ka. They further argue that these ages indicate an age of the Frankfurt phase of about 18 ka.

5.2 Pomeranian (W_2) and recessional phases

For the area ascribed to the Pomeranian and its recessional phases OSL ages of glaciofluvial sediments as well as SED ages of glacigenic boulders are available (Fig. 3): Lüthgens, Böse & Preusser (2011) dated glaciofluvial sediments from the Althüttendorf sandur, the Klosterbrücke outwash cone and from within the Eberswalde IMV; Heine et al. (2009) dated three samples from glacigenic boulders exposed in the Pomeranian terminal moraine; Brauer, Tempelhoff & Murray (2005) dated glaciofluvial sands exposed in the gravel pit Stolzenhagen; finally, Rinterknecht et al. (2010) dated samples from five erratic boulders from the Gerswalde terminal moraine, a recessional phase of the Pomeranian.

Lüthgens, Böse & Preusser (2011) applied single grain quartz OSL dating on four samples from the Althüttendorf sandur. This yields an average age of 20.1±1.6 ka for the deposition of glaciofluvial sediments on the outwash plain which is interpreted to represent the main sandur accumulation phase associated with the Pomeranian IMP. Three samples from the Klosterbrücke outwash fan near Eberswalde give an average age of 19.4±2.4 ka, interpreted to represent the latest accumulation of glaciofluvial sediments associated with the presence of an ice margin at the Pomeranian IMP. In addition Lüthgens, Böse & Preusser (2011) dated one sample from glaciofluvial sand incorporated within a succession of glaciolacustrine silt and clay accumulated within a depression formed by the melting of dead ice buried within the sediments of the Eberswalde IMV to 14.7±1.0 ka.

Heine et al. (2009) dated the exposure of three erratic boulders from the Pomeranian terminal moraine (Fig. 3) by SED using ^{10}Be. The observed scatter in ages, ranging from 17.7±0.9 ka to 15.4±0.6 (recalculated by Rinterkecht et al. 2010), is interpreted to indicate delayed stabilisation of the moraine surface after deglaciation. Following the argument of Reuther, Ivy-Ochs & Heine (2006) they further conclude that melting of buried dead ice may have caused post-depositional rotation and delayed exhumation, resulting in younger exposure ages which do not reflect the initial timing of the deglaciation (Heine et al. 2009). Despite this conclusion, these authors still argue that their ^{10}Be ages indicate a younger age of the Pomeranian moraine than previously reported for north-eastern Germany.

Based on the results from OSL dating of single aliquots of quartz, Brauer, Tempelhoff & Murray (2005) ascribe the major part of the sediment succession exposed in the sand pit near Stolzenhagen (~15 km north of the terminal moraines of the Pomeranian IMP, Fig. 3) to the Saalian glaciation (with ages ranging from 158±9 ka to 113±10 ka for 10 samples). Only the uppermost sample from a sand layer exposed below a till ascribed to the Brandenburg phase of the Weichselian glaciation shows a significantly younger age of 32.5±1.8 ka. The authors interpret this age to represent the deposition of proglacial sediments in the course of the ice advance of the SIS to its maximum extent during the Brandenburg phase. However, they sound a note of caution concerning the interpretation of the single OSL age, because they can not rule out age overestimation caused by incomplete resetting prior to deposition based on their multigrain single aliquot SAR measurements (Brauer, Tempelhoff & Murray 2005).

Rinterknecht et al. (2010) dated samples of five glacigenic boulders from the Gerswalde terminal moraine, a recessional moraine approximately 30 km north of the terminal moraines of the Pomeranian phase (Fig.3). Four of the samples were consistently dated to ~15 ka. One sample yielded a significantly lower age of 12.3±0.6 ka. The authors exclude this age as an outlier on a statistical basis (Chauvenet test), but do not provide a geomorphological explanation concerning possible causes for the delayed exposure of the boulder the sample was taken from. Based on the remaining four ages, which range from 14.8±0.8 ka to 15.8±0.9 ka, Rinterknecht et al. (2010) calculate an average exposure age of 15.2±0.5 ka which they interpret to represent the depositional age of the Gerswalde terminal moraine. They also calculated an average exposure age of 16.4±0.7 ka for the three boulders from the Pomeranian terminal moraine primarily dated by Heine et al. (2009). Based on these ages these authors argue that the ice advance of the Pomeranian phase occurred later than previously estimated and may be attributed to a re-advance of the SIS margin during the initial warming phase subsequent to Heinrich event 1 (H1, ~17 ka) in the North Atlantic region, but before the abrupt warming at the onset of the Bølling.

6 Chronology of the main Weichselian IMPs in north-eastern Germany

As a synthesis of the presented dating results we propose a new chronology for the main Weichselian IMPs in north-eastern Germany (following the process based interpretation model for OSL and SED ages described in section 4). In the following also see Table 2 and Figure 4.

An advancing ice front of the SIS passed the Stolzenhagen area at 32.5±1.8 ka (maximum age, Brauer, Tempelhoff & Murray 2005) and reached its maximum extent after ~34 ka (maximum age, Lüthgens, Böse & Krbetschek 2010, Lüthgens et al. 2010), with first results from single grain quartz OSL indicating sandur accumulation associated with the Brandenburg IMP on the Beelitz outwash cone at 27.7±4.0 ka (Lüthgens 2011). Based on the available data, it remains unclear whether the SIS reached its maximum extent in north-eastern Germany in early MIS 2 or already in late MIS 3 (Figure 4A). Results of SED (Heine et al. 2009) indicate a stabilisation of the landscape surface north of the Brandenburg IMP between 21.5±1.1 ka and 18.9±0.9 ka, providing the minimum age of deglaciation for that area (Fig. 4B). Unfortunately, no numerical ages for glacigenic sediments associated with the Frankfurt phase are available yet. As already pointed out by Behrmann (1949/50), the geological composition of the landforms points to older differences in elevation (occurrence of push morainic features), but the morphological forms indicate a weak disintegration of covering ice. It may therefore also be likely that the landforms associated with the Frankfurt phase represent a patchwork of landforms of different age rather than a synchronous IMP. Sandur formation associated with the Pomeranian IMP was dated to 20.1±1.6 ka at Althüttendorf and 19.4±2.4 ka at Eberswalde (Klosterbrücke outwash fan) respectively (Figure 4C, Lüthgens, Böse & Preusser 2011). Final stabilisation of the Pomeranian terminal moraine earliest at 17.7±0.9 ka can be deduced from the SED ages of erratic boulders (Heine et al. 2009, Rinterknecht et al. 2010). A period of boulder stabilisation at 15.8±0.9 to 14.8±0.4 ka in the area of the Gerswalde terminal moraine (Rinterknecht et al. 2010) provides a minimum age for deglaciation within that area and indicates further retreat of the SIS ice margin during the Gerswalde subphase (Figure 4D). This phase of boulder stabilisation is in good temporal agreement with the ages obtained for the deposition of periglacial cover sediments at ~15 ka on the Beelitz outwash cone (Lüthgens et al. 2010) and on the outwash plains of the Pomeranian IMP in Mecklenburg-Vorpommern (Küster & Preusser 2009). It also coincides with the meltout of buried dead ice within glaciofluvial sediments of the Eberswalde IMV documented by the accumulation of glaciofluvial sediments within a developing dead ice depression near Macherslust at 14.7±1.0 ka (Lüthgens, Böse & Preusser 2011).

Based on these results, there is clear evidence for a twofold advance of the SIS in north-eastern Germany during the last glaciation (see Figure 4). The Brandenburg phase represents the maximum extent of the ice sheet sometime between 34-24 ka (LGM defined as maximum ice extent). The advance of the Pomeranian phase occurred at around ~20 ka, which coincides with the LGM defined as the occurrence of the maximum global ice volume during the Weichselian glaciation as reconstructed from the marine isotope record (e.g. Bard 1999). This is in good agreement with the findings of Johnsen, Olsen & Murray (2010) who have given evidence for an interstadial from 25–20 ka in western Norway based on OSL and radiocarbon dating, dividing a formerly proposed single maximum ice advance into two stadials. Within the dynamic system of the SIS these effects were most likely not restricted to its western part, but would also have affected other sectors (Johnsen, Olsen & Murray 2010). Taking a possible MIS 3 age of the Brandenburg phase into account, it may be correlated with the advance of the Klintholm ice stream in Denmark at about 32±4 ka (based on OSL and calibrated radiocarbon ages of inter-till deposits) as reconstructed by Houmark-Nielsen (2010). This author proposes that this Baltic ice advance took place under relatively mild interstadial conditions coinciding with Dansgaard-Oeschger events 7–5. It was possibly driven by effects of changes in regional glacier dynamics and external climatic forcing (primarily enhanced precipitation). Therefore the timing of this ice advance does not conflict with the occurrence of terrestrial organogenic sediments attributed to the Denekamp inter-

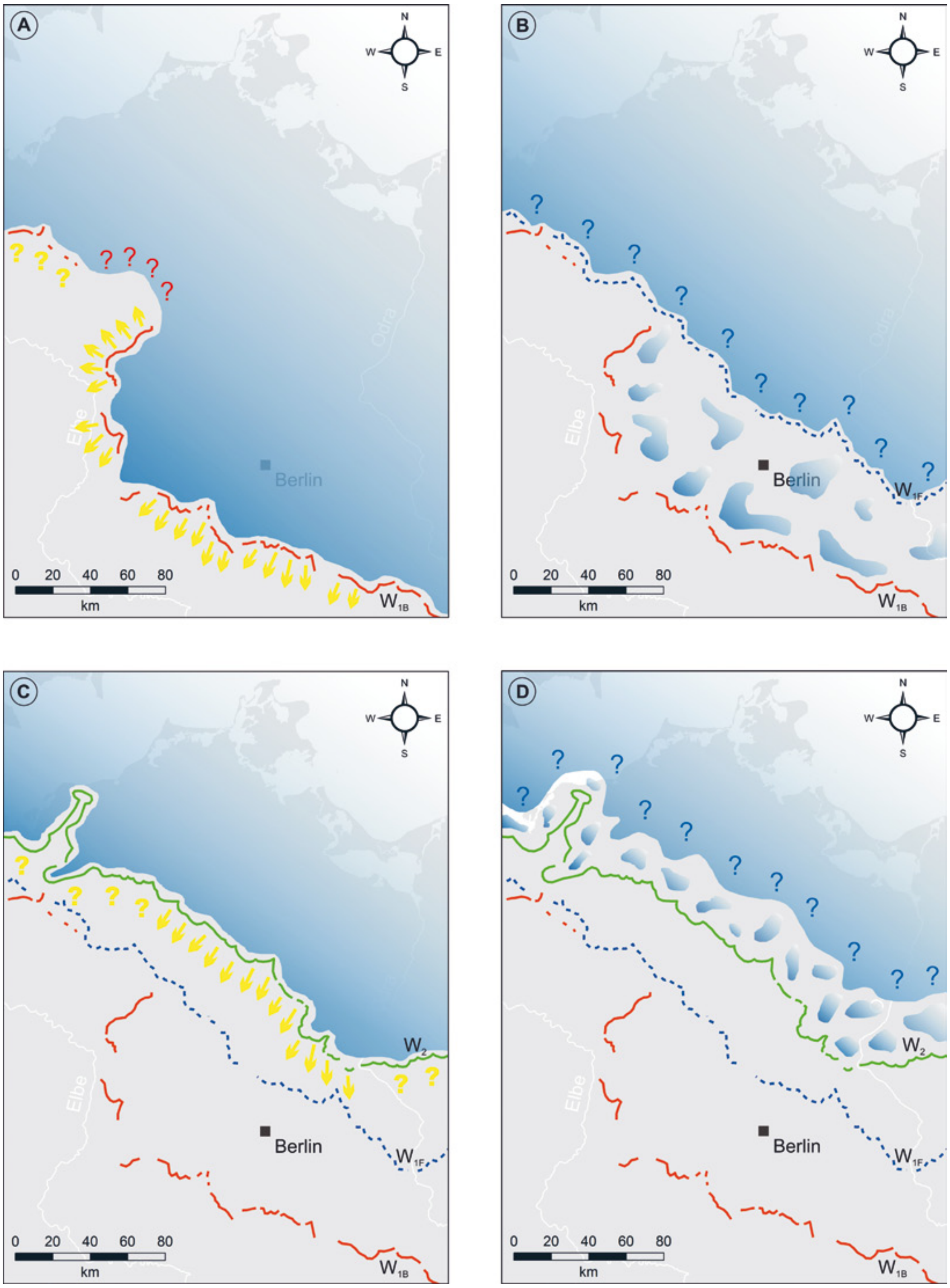

Fig. 4: For details concerning the base map we refer to the caption of figure 2. A) Extent of the SIS (blue shaded area) and position of the ice front at the Brandenburg IMP sometime between 34–24 ka implied by accumulation of glaciofluvial sediments on outwash plains (indicated by yellow arrows) dated by OSL (Lüthgens, Böse & Krbetschek 2010, Lüthgens et al. 2010, Lüthgens 2011). Unclear connections are indicated by question marks. B) Results from SED (Heine et al. 2009) provide a minimum age of >23 ka for the deglaciation (indicated by blue shaded patches) north of the Brandenburg IMP. However, it remains unclear how far the ice front had retreated at that time (possibly well north of the position indicated by blue question marks in the figure). C) Extent of the SIS and position of the ice front at the Pomeranian IMP at ~20 ka (based on results from OSL dating of sandur sediments, Lüthgens, Böse, & Preusser 2011). Correlations of the findings from Brandenburg with western Mecklenburg-Vorpommern and Schleswig-Holstein, as well as with Poland in the east remain unclear (indicated by yellow question marks). D) SED ages indicate initial deglaciation north of the Pomeranian IMP at least up to the Gerswalde IMP prior to 17 ka (Heine et al. 2009, Rinterknecht et al. 2010). The exact course of the SIS ice front at that time is still unclear.

Abb. 4: Für Details hinsichtlich der Kartengrundlage verweisen wir auf die Bildunterschrift von Abbildung 2. A) Ausdehnung des SIS (blau schattierter Bereich) und Lage des Eisrandes zu einem Zeitpunkt zwischen 34–24 ka, basierend auf OSL Datierungen (Lüthgens, Böse & Krbetschek 2010, Lüthgens et al. 2010, Lüthgens 2011) von Sandersedimenten. Unklare Verbindungen werden durch Fragezeichen markiert. B) Ergebnisse von Expositionsdatierungen (Heine et al. 2009) liefern ein Minimalalter für das Niedertauen und die Eisfreiwerdung (Gebiet mit blau schattierten Flecken) nördlich der Brandenburger Eisrandlage von >23 ka. Es bleibt jedoch unklar wie weit nördlich das Niedertauen zu diesem Zeitpunkt fortgeschritten war (möglicherweise deutlich weiter als auf der Abbildung durch Fragezeichen markiert). C) Ausdehnung des SIS und Lage des Eisrandes an der Pommerschen Eisrandlage um ca. ~20 ka (basierend auf Ergebnissen von OSL Datierungen von Sandersedimenten, Lüthgens, Böse & Preusser 2011). Die Korrelation der in Brandenburg gewonnenen Erkenntnisse mit dem westlichen Mecklenburg-Vorpommern und Schleswig-Holstein, sowie nach Osten hin mit Polen muss weiterhin als unklar angesehen werden (markiert durch gelbe Fragezeichen). D) Expositionsalter deuten auf eine Eisfreiwerdung nördlich der Pommerschen Eisrandlage mindestens bis zur Gerswalder Eisrandlage bereits vor 17 ka (Heine et al. 2009, Rinterknecht et al. 2010). Der genaue Verlauf des Eisrandes ist jedoch derzeit noch unklar.

Tab. 2: Summary of recent dating results of Weichselian glacigenic sediments in north-eastern Germany presented in (morpho)stratigraphical order.

Tab. 2: Zusammenfassung aktueller Datierungsergebnisse weichselzeitlicher glazigener Sedimente in Nord-Ost-Deutschland geordnet nach ihrer (morpho)stratigraphischen Position.

Site (Index for Fig. 3)	Sediment type dated	Dating method	Event dated	Age (ka)	Reference
(1) Stolzenhagen	Glaciofluvial sand underlying W_{1B} till	Single aliquot quartz OSL (SAR)	Advance of the SIS towards the W_{1B} IMP	<32.5±1.8	Brauer, Tempelhoff & Murray 2005
(2) Beelitz	Proglacial glaciofluvial sand (sandur)	Single aliquot quartz OSL (SAR)	Sandur formation associated with the W_{1B} IMP	<34.1±3.0	Lüthgens et al. 2010
(2) Beelitz	Proglacial glaciofluvial sand (sandur)	Single grain quartz OSL (SAR)	Sandur formation associated with the W_{1B} IMP	27.7±4.0	Lüthgens 2011
(3) Luckenwalde	Proglacial glaciofluvial sand (sandur)	Single aliquot quartz OSL (SAR)	Sandur formation associated with the W_{1B} IMP	<34.4±7.0	Lüthgens, Böse & Krbetschek 2010
(4) Area in between the W_{1B} and W_{1F} IMPs	Erratic boulders	SED using ^{10}Be	Landscape stabilisation in the hinterland of the W_{1B} IMP	21.5±1.1 - 18.9±0.9[1]	Heine et al. 2009
(5) Althüttendorf	Proglacial glaciofluvial sand (sandur)	Single grain quartz OSL (SAR)	Main sandur formation associated with the W_2 IMP	20.1±1.6	Lüthgens, Böse & Preusser 2011
(6) Eberswalde	Proglacial glaciofluvial sand (sandur)	Single grain quartz OSL (SAR)	Final sandur formation associated with the W_2 IMP	19.4±2.4	Lüthgens, Böse & Preusser 2011
(7) Pomeranian terminal moraine	Erratic boulders	SED using ^{10}Be	Stabilisation of the Pomeranian terminal moraine	17.7±0.9 – 15.4±0.6[2]	Heine et al. 2009
(8) Gerswalde terminal moraine	Erratic boulders	SED using ^{10}Be	Stabilisation of the Gerswalde terminal moraine	15.8±0.9 – 14.8±0.4[2]	Rinterknecht et al. 2010
(9) Macherslust	Glaciofluvial sand	Single grain quartz OSL (SAR)	Accumulation of glaciofluvial sediments within a develo-ping dead ice depression	14.7±1.0	Lüthgens, Böse & Preusser 2011

1 Ages recalculated from original data provided in Heine et al. (2009) to the Lal (1991)/Stone (2000) (Lm) scaling scheme without corrections for snow cover, vegetation cover and erosion using the CRONUS-Earth online ^{10}Be exposure age calculator version 2.2 (http://hess.ess.washington.edu/math) (Balco et al. 2008).

2 Ages recalculated by Rinterknecht et al. (2010)

stadial (~30 ka (cal.), Litt et al. 2007) based on palynological findings and radiocarbon dating. However, we advise caution concerning the interpretation of the first few numerical ages available from the Brandenburg phase. Although different scenarios may seem plausible (including an MIS 3 advance), additional investigations are necessary to further clarify the age of the W_{1B} ice advance.

Marks (2010) discussed the concept of an MIS 3 ice advance for Poland based on his reinterpretation of ^{36}Cl SED ages of Dzierzek & Zreda (2007). Inferred from results of cosmogenic dating of erratic boulders and landscape surfaces using ^{36}Cl, Dzierzek & Zreda (2007) provide an age of 27–28 ka for the initial deglaciation after the first ice advance in north-eastern Poland. However, Marks (2010) provides a maximum age of 24 ka for the Lezno phase in Poland which is usually correlated with the Brandenburg phase in Germany. This age estimate is based on a number of radiocarbon ages clustering around 25 ka (cal.) derived from peat underlying the glacigenic sediments in the area of Konin and from organic silts in the Pomeranian bay (Baltic Sea). These ages may correlate well with the interstadial proposed by Johnsen, Olsen & Murray (2010). However, they impede a direct correlation of the chronology for north-eastern Germany with that of Poland. The determination of the yet unknown chronostratigraphical position of the Frankfurt phase in Germany may help to solve this issue.

Due to the time transgressive nature of morphostratigraphically defined IMPs (Marks 2002, Lüthgens & Böse 2010), we refrain from any correlations with available SED data for the LGM from Lithuania and Belarus (Rinterknecht et al. 2006a, 2007, 2008). The age of the Pomeranian phase in Poland has mainly been based on the results from SED using ^{10}Be (Rinterknecht et al. 2005, 2006a). Lüthgens, Böse & Preusser (2011) provide a detailed discussion on the reassessment of these ages with respect to the process-based interpretation model described above. For this review we will therefore only focus on the SED ages obtained from the Pomeranian phase in western Poland. Excluding low outliers exposed during the Holocene, eight SED ages are available ranging from 18.0±1.3 ka to 10.8±0.8 ka with ages clustering around ~15 ka. Given their widespread dispersion in western Poland (distances of >100 km between individual boulders, cf. Marks 2010: Fig. 7) their geochronological significance for the age of the Pomeranian moraine seems questionable. However, the sample from the boulder situated closest to the Pomeranian IMP also yields the oldest age of 18.0±1.3 ka, which is in perfect agreement with the phase of boulder stabilisation of the Pomeranian terminal moraine in north-eastern Germany based on the SED ages of Heine et al. (2009).

In addition, there is now geochronometrical evidence (Brauer, Tempelhoff & Murray 2005, Lüthgens, Böse & Krbetschek 2010) that the ice advance to the Brandenburg IMP only reshaped a relief initially generated by the Saalian glaciation. Lüthgens, Böse & Krbetschek (2010) further suggest that transformation of the relief was mainly linked to meltwater processes, implying a fast-paced and short-lived ice advance. In contrast, the ice advance during the Pomeranian phase shaped the most prominent ice marginal features (terminal moraines and outwash plains) in north-eastern Germany. Lüthgens (2011) points out that these different characteristics in ice dynamics are additionally deducible from the different luminescence characteristics observed for glaciofluvial sediments associated with both phases. Although taken from identical depositional environments, all samples from the Brandenburg phase showed incomplete resetting of the OSL signal, whereas the majority of samples from the Pomeranian IMP did not suffer from that problem. Lüthgens (2011) suggests that this may indicate a very limited reworking of the glaciofluvial sediments on the elevated outwash cones of the Brandenburg IMP, with meltwater flow quickly shifting to the incised fluvioglacial channel system.

Finally, we would like to point out that first OSL ages for the deposition of periglacial cover-sediments may point toward an activity phase at ~15 ka (Beelitz outwash cone – Lüthgens et al. 2010, Pomeranian outwash plain – Küster & Preusser 2009). This coincides with age clusters observed from SED datasets indicating increased exposure of glacigenic boulders at that time (Gerswalde subphase – Rinterknecht et al. 2010, areas ascribed to the Pomeranian phase in north-eastern Germany, Poland, Lithuania, Latvia, Belarus – Heine et al. 2009, Rinterknecht et al. 2005, 2006a, 2007, 2008). Lüthgens, Böse & Preusser (2011) recently verified the statistical significance of that age cluster for a dataset containing all SED ages available from the Pomeranian phase. As proposed by Küster & Preusser (2009) this activity phase at ~15 ka correlates well with the formation of the Beuningen gravel bed (BGB) which serves as an important marker horizon in the late Weichselian coversand stratigraphy of Western Europe (Vandenberghe 1985, Kasse 2002). Kasse at al. (2007) provide bracketing ages of 17.2±1.2 ka and 15.3±1.0 ka for the formation of the BGB in the southern Netherlands based on results from OSL dating of quartz and propose a correlation with Heinrich event H1. However, the implied correlation of the formation of the BGB, the formation of periglacial cover-sediments, and the enhanced exposure of erratic boulders needs further investigation in order to be reliably validated. The age of 14.7±1.0 ka from the Macherslust section (Lüthgens, Böse & Preusser 2011) may serve as a first geochronological marker for the meltout of buried dead ice in north-eastern Germany at the onset of the Meiendorf and the subsequent Bølling warming period, but the question when dead ice finally melted remains to be specified.

Within this review we summarised the newly available numerical ages for Weichselian glacigenic sediments from north-eastern Germany and propose a new chronology for the main Weichselian ice marginal positions. However, as already pointed out by Lüthgens (2011) a range of open questions remains to be answered. Firstly, the exact timing of the Brandenburg IMP needs to be specified in order to finally give evidence for its geochronological assignment to either MIS 2 or MIS 3. Secondly, the geochronological position of the Frankfurt IMP and the question of its morphostratigraphical integrity remain to be clarified. Finally, geochronometrical data for recessional IMPs, especially north of the Pomeranian IMP, need to be obtained in order to be able to fully reconstruct the deglaciation pattern of the Weichselian SIS in north-eastern Germany from its maximum extent at the Brandenburg IMP to its northward retreat beyond the recent shoreline of the Baltic Sea.

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8 References

Balco, G., Stone, J.O., Lifton, N.A. & Dunai, T.J. (2008): A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. – Quaternary Geochronology, 3: 174–195.

Bard, E. (1999): Ice Age Temperatures and Geochemistry. – Science, 284: 1133–1134.

Bailey, R.M. & Arnold, L.J. (2006): Statistical modelling of single grain quartz De distributions and an assessment of procedures for estimating burial dose. – Quaternary Science Reviews, 25: 2475–2502.

Behrmann, W. (1949/50): Die Umgebung Berlins nach morphologischen Formengruppen betrachtet. – Die Erde, 1: 93–122.

Böse, M. (1994): Ice margins and deglaciation in the Berlin area between Brandenburg and Frankfurt end moraines – a review. – Zeitschrift für Geomorphologie N.F., Suppl. 95: 1–6.

Böse, M. (2005): The Last Glaciation and Geomorphology. – In: Koster, E.A. (ed.): The Physical geography of Western Europe: 61–74; Oxford University Press.

Bøtter-Jensen, L., McKeever, S.W.S. & Wintle, A.G. (2003): Optically Stimulated Luminescence Dosimetry. – Elsevier, Amsterdam.

Brauer, A., Tempelhoff, K. & Murray, A. (2005): OSL Dating of Fine-Grained Sand Deposits and its Implications for Glacial Stratigraphy and Landscape Evolution: Research Results from Stolzenhagen, North-eastern Brandenburg. – Die Erde, 136: 15–35.

Brose, F. (1995): Erscheinungen des weichselzeitlichen Eisrückzuges in Ostbrandenburg. – Brandenburgische Geowissenschaftliche Beiträge, 1995 (1): 3–11.

Cepek, A.G. (1965): Die Stratigraphie der pleistozänen Ablagerungen im Norddeutschen Tiefland. – In: Gellert, J.F. (ed.): Die Weichsel-Eiszeit im Gebiet der DDR: 45–65.

Duller, G.A.T. (2008): Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. – Boreas, 37: 589–612.

Dzierzek, J. & Zreda, J. (2007): Timing and style of deglaciation of northeastern Poland from cosmogenic ^{36}Cl dating of glacial and glaciofluvial deposits. – Geological Quarterly, 51-2: 203–216.

Ehlers, J. & Gibbard, P.L. (eds.) (2004): Quaternary Glaciations – Extent And Chronology – Part I: Europe. – Elsevier; Amsterdam.

Everest, J. & Bradwell, T. (2003): Buried glacier ice in southern Iceland and its wider significance. – Geomorphology, 52: 347–358.

Fuchs, M. & Owen, L.A. (2008): Luminescence dating of glacial and associated sediments: review, recommendations and future directions. – Boreas, 37: 636–659.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H. & Olley, J.M. (1999): Optical dating of single and multiple grains of Quartz from Jinmium rock shelter, northern Australia: Part I, experimental design and statistical models. – Archaeometry, 41: 339–364.

Gosse, J.C. & Phillips, F.M. (2001): Terrestrial in situ cosmogenic nuclides: Theory and application. – Quaternary Science Reviews, 20: 1475–1560.

Heine, K., Reuther, A.U., Thieke, H.U., Schulz, R., Schlaak, N. & Kubik, P.W. (2009): Timing of Weichselian ice marginal positions in Brandenburg (northeastern Germany) using cosmogenic in situ 10Be. – Zeitschrift für Geomorphologie N.F., 53 (4): 433–454.

Houmark-Nielsen, M., Björck, S. & Wohlfarth, B. (2006): 'Cosmogenic 10Be ages on the Pomeranian Moraine, Poland': Comments. – Boreas, 35: 600–604.

Houmark-Nielsen, M. (2010): Extent, age and dynamics of Marine Isotope Stage 3 glaciations in the southwestern Baltic Basin. – Boreas, 39: 343–359.

Ivy-Ochs, S. & Kober, F. (2008): Surface exposure dating with cosmogenic nuclides. – Eiszeitalter und Gegenwart, 57 (1/2): 179–209.

Jarvis, A., Reuter, H.I., Nelson, A. & Guevara, E. (2006): Hole-filled seamless SRTM data V3. – International Centre for Tropical Agriculture (CIAT); available from http://srtm.csi.cgiar.org.

Juschus, O. (2001): Das Jungmoränenland südlich von Berlin – Untersuchungen zur jungquartären Landschaftsentwicklung zwischen Unterspreewald und Nuthe, (dissertation at the Humboldt Universität zu Berlin). http://edoc.hu-berlin.de/dissertationen/juschus-olaf-2001-05-04/PDF/Juschus.pdf. 251 p; Berlin.

Johnsen, F.J., Olsen, L. & Murray, A.S. (2010) in press: OSL ages in central Norway support a MIS 2 interstadial (25–20 ka) and a dynamic Scandinavian ice sheet. – Quaternary Science Reviews: DOI: 10.1016/j.quascirev.2010.10.007

Kasse, C. (2002): Sandy aeolian deposits and environments and their relation to climate during the Last Glacial Maximum and Lateglacial in northwest and central Europe. – Progress in Physical Geography, 26: 507–532.

Kasse, C., Vandenberghe, J., de Corte, F. & Haute van den, P. (2007): Late Weichselian fluvio-aeolian sands and coversands of the type locality Grubbenvorst (southern Netherlands): sedimentary environments, climate record and age. – Journal of Quaternary Science, 22/7: 695–708.

Keilhack, K. (1909): Begleitworte zur Karte der Endmoränen und Urstromtäler Norddeutschlands. – Jahrbuch der Königlich Preussischen geologischen Landesanstalt und Bergakademie zu Berlin, 30 (1): 507–510.

Kliewe, H. & Jahnke, W. (1972): Verlauf und System der Marginalzonender letzten Vereisung auf dem Territorium der DDR. – Wissenschaftliche Zeitschrift der Erns-Moritz-Arndt-Universität Greifswald – Mathematisch-Naturwissenschaftliche Reihe, 21: 31–37.

Kozarski, S. (1992): Eine auf der Radiokarbonmethode basierende Abschätzung der Rückzugschronologie des letzten Inlandeises in Nordpolen. – In: Billwitz, K., Jäger, K.D. & Janke, W. (eds.): Jungquartäre Landschaftsräume: 16–22; Berlin.

Kozarski, S. (1995): Deglacjacja północno-zachodniej Polski: womki i trasformacja geosystema (~20 ka–10 ka). – Documentacja Geograficzna 82.

Küster, M. & Preusser, F. (2009): Late Glacial and Holocene aeolian sands and soil formation from the Pomeranian outwash plain (Mecklenburg, NE-Germany). – E&G Quaternary Science Journal, 58: 156–163.

Lal, D. (1991): Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. – Earth and Planetary Science Letters, 104: 424–439.

Lian, O. B. & Roberts, R. G. (2006): Dating the Quaternary: progress in luminescence dating of sediments. – Quaternary Science Reviews, 25: 2449–2468.

Libby, W.F. (1952): Radiocarbon Dating. – University of Chicago Press; Chicago.

Liedtke, H. (1975): Die Nordischen Vereisungen in Mitteleuropa. – Forschungen zur deutschen Landeskunde, 204; Bonn.

Liedtke, H. (1981): Die Nordischen Vereisungen in Mitteleuropa. – Forschungen zur deutschen Landeskunde, 204 (2nd edition); Trier.

Liedtke, H. (1996): Die eiszeitliche Gestaltung des Oderbruchs. – Heidelberger Geographische Arbeiten, 104: 327–351.

Liedtke, H. (2001): Das nordöstliche Brandenburg während der Weichseleiszeit. – In: Bussemer, S. (ed.): Das Erbe der Eiszeit: 119–133; Langenweißbach.

Lippstreu, L. (1995): Brandenburg. – In: Benda, L. (ed.): Das Quartär Deutschlands: 116–147; Berlin.

Litt, T., Behre, K.-E., Meyer, K.-D., Stephan, H.-J. & Wansa, S. (2007): Stratigraphische Begriffe für das Quartär des norddeutschen Vereisungsgebietes. – In: Litt, T. (ed.): Stratigraphie von Deutschland – Quartär. – E&G Quaternary Science Journal, 56: 7–65.

Lüthgens, C. (2011): The age of Weichselian main ice marginal positions in north-eastern Germany inferred from Optically Stimulated Luminescence (OSL) dating. – PhD thesis, Freie Universität Berlin, available from: http://www.diss.fu-berlin.de/diss/receive/FUDISS_thesis_000000022882

Lüthgens, C. & Böse, M. (2010) in press: From morphostratigraphy to geochronology – on the dating of ice marginal positions. – Quaternary Science Reviews, DOI: 10.1016/j.quascirev.2010.10.009

Lüthgens, C., Böse, M. & Krbetschek, M.R. (2010): On the age of the young morainic morphology in the area ascribed to the maximum extent of the Weichselian glaciation in north-eastern Germany. – Quaternary International, 222: 72–79.

Lüthgens, C., Böse, M. & Preusser, F. (in press): Age of the Pomeranian ice marginal position in north-eastern Germany determined by Optically Stimulated Luminescence (OSL) dating of glaciofluvial sediments. – Boreas, DOI: 10.1111/j.1502-3885.2011.00211.x

Lüthgens, C., Krbetschek, M.R., Böse, M. & Fuchs, M.C. (2010): Optically Stimulated Luminescence Dating of fluvioglacial (sandur) sediments from north-eastern Germany. – Quaternary Geochronology, 5: 237–243.

Lüttig, G. (2005): Geschiebezählungen im westlichen Mecklenburg. – Archiv für Geschiebekunde, 4: 569–600.

Marks, L. (2002): Last Glacial Maximum in Poland. – Quaternary Science Reviews, 21: 103–110.

Marks, L. (2010) in press: Timing of the Late Vistulian (Weichselian) glacial phases in Poland. – Quaternary Science Reviews, DOI:10.1016/j.quascirev.2010.08.008

Murray, A.S. & Wintle, A.G. (2000): Luminescence dating of Quartz using an improved single aliquot regenerative dose protocol. – Radiation Measurements, 32: 57–73.

Murray, A.S. & Wintle, A.G. (2003): The single aliquot regenerative dose protocol: potential for improvements in reliability. – Radiation Measurements, 37: 377–381.

Penck, A. (1879): Die Geschiebeformation Norddeutschlands. – Zeitschrift der Deutschen Geologischen Gesellschaft, 31: 117–203.

Penck, A. (1882): Die Vergletscherung der deutschen Alpen: ihre Ursachen, periodische Wiederkehr und ihr Einfluss auf die Bodengestaltung. – Barth; Leipzig.

Preusser, F., Degering, D., Fuchs, M., Hilgers, A., Kadereit, A., Klasen, N., Krbetschek, M., Richter, D. & Spencer, J.Q.G. (2008): Luminescence dating: basics, methods and applications. – E&G Quaternary Science Journal, 57: 95–149.

Reuther, A.U., Ivy-Ochs, S. & Heine, K. (2006): Application of surface exposure dating in glacial geomorphology and the interpretation of moraine ages. – Zeitschrift für Geomorphologie N.F., 142: 335–359.

Rinterknecht, V.R., Bitinas, A., Clark, P.U., Raisbeck, G.M., Yiou, F. & Brook, E.J. (2008): Timing of the last deglaciation in Lithuania. – Boreas, 37: 426–433.

Rinterknecht, V.R., Braucher, R., Böse, M., Bourlès, D. & Mercier, J.-L. (2010) in press: Late Quaternary ice sheet extents in northeastern Germany inferred from surface exposure dating. – Quaternary Science Reviews, DOI: 10.1016/j.quascirev.2010.07.026

Rinterknecht, V.R., Clark, P.U., Raisbeck, G.M., Yiou, F., Bitinas, A., Brook, E.J., Marks, L., Zelčs, V., Lunkka, J.-P., Pavlovskaya, I.E., Piotrowski, J.A. & Raukas, A. (2006a): The Last Deglaciation of the Southeastern Sector of the Scandinavian Ice Sheet. – Science, 311: 1449–1452.

Rinterknecht, V.R., Marks, L., Piotrowski, J., Raisbeck, G.M., Yiou, F., Brook, E.J. & Clark, P.U. (2005): Cosmogenic ^{10}Be ages on the Pomeranian Moraine, Poland. – Boreas, 34: 186–191.

Rinterknecht, V.R., Marks, L., Piotrowski, J., Raisbeck, G. M., Yiou, F., Brook, E.J. & Clark, P.U. (2006b): 'Cosmogenic ^{10}Be ages on the Pomeranian Moraine, Poland': Reply to comments. – Boreas, 35: 605–606.

Rinterknecht, V.R., Pavlovskaya, I.E., Clark, P.U., Raisbeck, G. M., Yiou, F. & Brook, E.J. (2007): Timing of the last deglaciation in Belarus. – Boreas, 36: 307–313.

Stone, J.O. (2000): Air pressure and cosmogenic isotope production. – Journal of Geophysical Research, 105: 753–23, 759.

Stuiver, M., Reimer, P. J., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, G., der Plicht, V. J., & Spurk, M. (1998): INTCAL98 radiocarbon age calibration 24000–0 cal BP (1950). – Radiocarbon, 40: 1041–1083.

Terberger, T., Klerk, P. de, Helbig, H., Kaiser, K. & Kühn, P. (2004): Late Weichselian landscape development and human settlement in Mecklenburg-Vorpommern (NE Germany). – Eiszeitalter und Gegenwart, 54: 138–175.

Thrasher, I.M., Mauz, B., Chiverrell, R.C. & Lang, A. (2009): Luminescence dating of glaciofluvial deposits: A review. – Earth-Science Reviews, 97: 133-146.

Torell, O. (1875): Ueber das norddeutsche Diluvium. In: Beyrich, V., Rammelsberg & W., Weiss, O.: Verhandlungen der Gesellschaft – Protokoll der November-Sitzung. – Zeitschrift der Deutschen Geologischen Gesellschaft, 27: 958–962.

Vandenberghe, J. (1985): Paleoenvironment and stratigraphy during the Last Glacial in the Belgian-Dutch Border Region. – Quaternary Research, 24: 23–38.

Wintle, A.G. (2008a): Fifty years of luminescence dating. – Archaeometry, 50: 276–312.

Wintle, A.G. (2008b): Luminescence dating. Where it has been and where it is going. – Boreas, 37: 471–482.

Wintle, A.G. & Murray, A.S. (2006): A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. – Radiation Measurements, 41: 369–391.

Woldstedt, P. (1925): Die großen Endmoränenzüge Norddeutschlands. – Zeitschrift der Deutschen Geologischen Gesellschaft, 77: 172–184.

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Deglaciation of a large piedmont lobe glacier in comparison with a small mountain glacier – new insight from surface exposure dating. Two studies from SE Germany

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Abstract: ^{10}Be surface exposure ages of moraine boulders deposited during the maximum Würmian ice extent and the deglaciation period in two different glacial environments show different age distributions despite similar climatic boundary conditions. A consistent and precise late Würmian chronostratigraphy was derived from deposits of a small valley glacier in the Bavarian Forest. Exposure ages from terminal moraines of the Isar-Loisach and the Inn glacier in the Eastern Alps indicate a moraine deposition well before 18.0±1.9 ka and moraine stabilization throughout the late glacial. Both glacial systems reached their maximum Würmian ice extent during the late Würmian. Despite this broad synchronicity, the response time to climatic fluctuations of the valley glacier in comparison to that of the piedmont glacier system is different, with the valley glacier being more sensitive to climatic signals. Synchronicity of the late glacial readvance in the Bavarian Forest and the Eastern Alps was reached during 16–15 ka (Gschnitz advance), when only valley glaciers existed in both regions. The age distributions determined for either of these glacial environments originate likely in glacier ice dynamics and geomorphic processes affecting moraine stabilization acting differently in each setting. Our data gives insight into landscape stability and moraine degradation in different glacial environments and has implications for sampling strategies and data interpretation for glacial exposure ages.

[Deglaziation eines großen Vorlandgletschers im Vergleich mit einem kleinen Gebirgsgletscher – neue Erkenntnisse aufgrund von Oberflächenexpositionsaltern. Zwei Studien aus Südost-Deutschland]

Kurzfassung: ^{10}Be-Oberflächenaltersdatierungen von Moränenblöcken der Würm-Maximalvergletscherung und der Deglaziationzeit ergaben in zwei verschiedenen Regionen Süddeutschlands unterschiedliche Altersverteilungen trotz gleicher klimatischer Randbedingungen. Im Bayerischen Wald zeigen die Moränenalter eines kleinen Talgletschers eine präzise und konsistente spätwürmzeitliche Chronostratigraphie. Oberflächenexpositionsalter von Moränen des Isar-Loisach und Inngletschers in den Ostalpen weisen auf eine hochwürmzeitliche Moränenablagerung deutlich vor 18.0±1.9 ka und einer anschliessenden Moränenstabilisierung hin. Beide glaziale Systeme (Mittelgebirgs-Talgletscher und alpines Eisstromnetz) erreichten ihre maximale Ausdehnung im Spätwürm (MIS 2). Trotz der weitgehenden Übereinstimmung war ihre Reaktionszeit auf Klimafluktuationen sehr unterschiedlich: der kleine Talgletscher reagierte empfindlicher auf klimatische Änderungen als das alpine Eisstromnetz. Ein synchrones Verhalten zeigten die Gletscher im Bayerischen Wald sowie in den Ostalpen erst im Spätglazial um 16–15 ka (H 1), als in beiden Gebieten Talgletscher existierten. Die unterschiedlichen Altersverteilungen der spätwürmzeitlichen Chronologien in den beiden Würmgletscher-Endmoränengebieten werden mit Unterschieden der Eisdynamik und der geomorphologischen Prozesse bei der Moränenstabilisierung sowie mit Phasen intensiver Hangprozesse infolge periglazialer Aktivität und Toteis-Tauens erklärt. Die Ergebnisse sind für Probennahmestrategien und Dateninterpretation von Moränen-Oberflächenaltern von großer Bedeutung.

Keywords: *Bavarian Forest, Eastern Alps, Inn glacier, Isar-Loisach glacier, Würm type section, cosmogenic dating, moraine degradation, dead ice*

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1 Introduction

Glacial landscapes are one of the classical study areas for surface exposure dating with terrestrial in-situ produced cosmogenic nuclides (TCND) (Phillips et al. 1990; Gosse et al. 1995a, b; Cockburn & Summerfield 2004). The method is frequently applied to constrain glacial chronologies based on exposure ages of moraine boulders (Reuther et al. 2006). However, the age distributions that are determined in moraine dating studies do not always reflect the landform age (Reuther et al. 2006, Heine, 2011). The scatter that is found in these datasets is often greater than statistically expected from the associated errors and frequently biased or polymodal age distributions are determined (Putkonen & Swanson 2003). This scatter is likely explained by geomorphological processes such as for example multiple glacial advances or post-depositional degradation of moraines (Zreda et al. 1994; Briner et al. 2005; Zech et al. 2005; Putkonen & O'Neal 2006). In glacial environments the assumptions underlying the TCND technique are often not valid because (1) moraines that contain dead ice or that are exposed to intensive periglacial slope

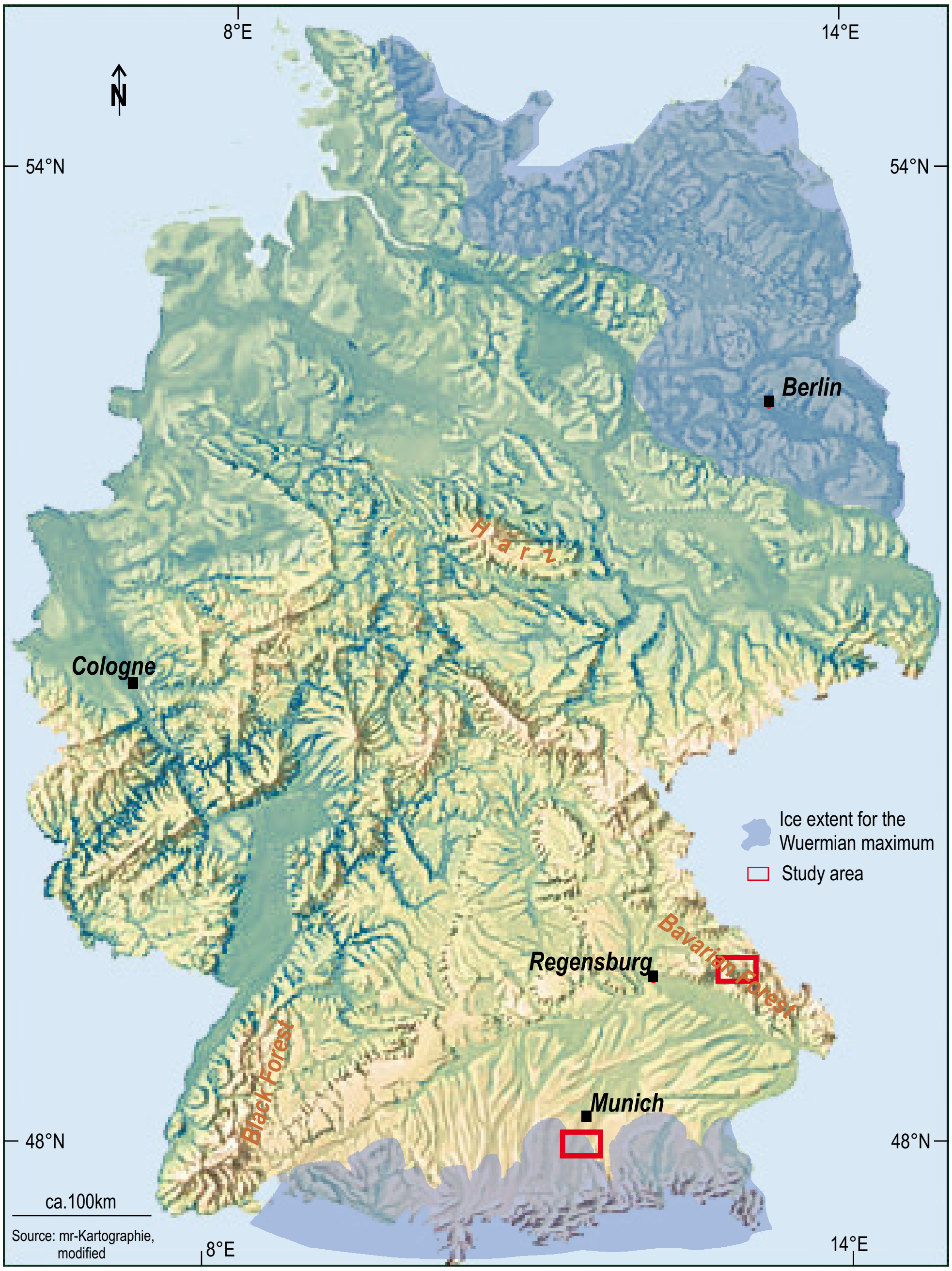

Fig. 1: Shaded relief of Germany showing the late Weichselian/Würmian ice extent and the periglacial corridor between the two ice masses. Study areas are marked with red boxes.

Abb. 1: Reliefdarstellung der spät-Weichsel/Würm-zeitlichen Eisausdehnung in Deutschland und des periglazialen Korridors zwischen den beiden Eismassen. Die Untersuchungsgebiete sind jeweils mit einem roten Kasten markiert.

processes are unstable landforms at the timescales of 10^2 to 10^3 years and (2) moraine boulders do sometimes carry inherited nuclide abundance. In these cases non-Gaussian exposure age distributions are determined from moraine boulders. Furthermore, the glacier type (e.g. valley glaciation or continental ice sheets; warm-based or cold-based) and the climatic boundary conditions (arid or humid; tropical or arctic) influence moraine stability or degradation and thus the exposure age distributions from moraine boulders (Evans 2004).

Models of moraine degradation or boulder exhumation have been published that help understanding and quantifying the principles of surface processes (Zreda et al. 1994; Hallet & Putkonen 1994; Zreda & Phillips 1995; Putkonen & Swanson 2003). However, the depositional environment of each moraine boulder and the climatic boundary conditions that affected the moraine during and after deposition have not yet been incorporated in the models but need to be considered in the data interpretation.

In any glacial environment, exposure ages from boulders on moraines will yield the time of landform stabilization; the probability of inherited nuclide concentration is only a few percent (Putkonen & Swanson 2003). A valley glacier with negligible debris cover often leaves behind simple, well preserved moraine sequences (Heim 1885). In contrast, at the ice margin of extensive ice lobes, dead ice bodies are often disconnected from the active glacier during deglaciation. These debris-covered dead ice bodies or ice-cored moraines will persist until climatic conditions are favourable enough for their thawing causing intensive moraine degradation (Gripp & Ebers 1957; Dyke & Savelle 2000; Everest & Bradwell 2003).

In this study we exposure dated moraine boulders in different glacial environments (piedmont shaped outlet lobes from central Alpine ice caps versus small valley glacier system in the Bavarian Forest) that were affected by similar climatic boundary conditions during the late Pleistocene. This research setup allows testing the hypothesis of variations in exposure age distributions on moraines due to different glacial environments. Central Europe is an ideal study area to address this research question, as different glacial environments can be found in close proximity.

During the Würmian last glacial maximum the central European climatic regime was strongly influenced by the large Scandinavian ice sheet extending far into Northern Germany (Ehlers et al. 2004; Heine et al. 2009) as well as the Alpine ice cap with its extensive ice domes, its inner-alpine network of large interconnected valley glaciers and outlet glaciers that spread out as extensive piedmont lobes onto the Alpine foreland (Penck & Brückner 1901/09; van Husen 1997; Florineth & Schlüchter 1998; Kelly et al. 2004). A 500 km wide periglacial corridor extended between these two large ice masses (Fig. 1). Only a few isolated mountain ranges carried small mountain glaciers, as for instance the Black Forest, the Vosges, the Bavarian Forest and the Harz Mountains (Fig. 1; Seret et al. 1990; Rother 1995).

Numerous chronological studies have bracketed the timing of glacial advances in the Alps and in the area covered by the Scandinavian ice sheet, indicating that both large ice masses reached their last glacial maximum ice extent coeval during the late Würmian, respectively late Weichselian (e.g. Ehlers & Gibbard 2004a). Terrestrial glacial chronologies for low mountainous areas of central Europe (Mittelgebirge) are still patchy and no coherent numerical glacial chronology for any of the mountain ranges has yet been established (e.g. Rother 1995). Cosmogenic ages of moraines will considerably advance the age control of glaciations as the method allows direct dating of glacial deposition and thus supplements the bracketing radiocarbon ages.

As study sites we chose the respective type sections of the Eastern Alpine piedmont glaciation and the small mountain glaciation in the Bavarian Forest in south-eastern Germany. The Bavarian Forest is located only some 160 km north/northeast of the terminal moraines of the Alpine piedmont glaciers (Fig 1).

In the Eastern Alps, a type section of the Würmian glaciation is the sequence of glacial deposits around the Würmsee (now called Starnberger See) deposited by the former Isar-Loisach glacier (Chaline & Jerz 1984). This sequence of glacial deposits was eponymous for the Würm glaciation (Penck & Brückner 1901/09) and has been intensively mapped and studied (e.g. Penck & Brückner 1901/09; Troll 1937; Rothpletz 1917; Jerz 1987a, b; Feldmann 1992). Up to now, no numerical ages constrain the chronology of these glacial deposits.

The glacial sequence around the Kleiner Arbersee is typical for the late Würmian glaciation in the Bavarian Forest (Partsch 1882; Penck et al. 1887; Jerz 1993). The deposits of this sequence are well mapped (Bayberger 1886; Rathsburg 1928, 1930; Priehäusser 1927, 1930; Bucher 1999) and have been sedimentologically studied in detail (Hauner 1980; Mahr 1998; Raab 1999; Raab & Völkel 2003). However, only a few radiocarbon dates yield minimum ages for the regional deglaciation (Raab & Völkel 2003).

The goal of our study was two-fold: Firstly, we aimed to establish a numerical chronology for the Würmian glaciation at the respective type localities in the Eastern Alps and the Bavarian Forest mountain range which are numerically undated sites, and secondly, we aimed to compare the validity of surface exposure dating in two very different glacial settings (Alpine piedmont glacier on foreland versus small valley glacier system in Bavarian Forest).

In the first part of this paper the results from the numerical dating studies for both field areas are presented. In the second part the implications of our studies for surface exposure dating in different glacial settings are discussed.

2 Materials and Methods

19 boulder and bedrock samples were taken in the Bavarian Forest from gneiss surfaces. 10 crystalline boulder surfaces were sampled on the Alpine foreland moraines. Geographic coordinates and topographic shielding were measured using a GPS receiver and a hand-held inclinometer, respectively (Tab. 1, 2).

The samples were crushed and ground and the quartz fraction was separated following the procedures described by Kohl & Nishiizumi (1992) and Ivy-Ochs (1996). BeO was extracted using a combination of column chemistry separation and selective hydroxide precipitations (Ochs & Ivy-Ochs 1997). Ratios of the radionuclide to the stable nuclide were measured using accelerator mass spectrometry (AMS) at the ETH Zurich tandem accelerator facility (Synal et al. 1997). Apparent exposure ages were calculated from the measured nuclide concentration, the site-specific production rate according to Lal (1991) and Stone (2000) and the sampling depth. They were corrected for topographic shielding (Dunne et al. 1999), variations in the geomagnetic field (Laj et al. 2004), erosion, uplift, snow and vegetation cover (Gosse & Phillips 2001). The dense forest canopy inhibited field measurements of the topographic shielding in the Bavarian Forest. Shielding angles for each sample were calculated with a Geographic Information System (GIS) based on spatial information obtained from a high-resolution DEM (Reuther 2007). The following aspects were considered for the corrections:

Bavarian Forest:

(i) The exposure ages were calculated using an erosion rate of 5±2 mm ka^{-1} based on measurements in the field, a value that is in agreement with values used in similar studies (appendix 1).

(ii) Snow cover is significant (Fig. 2). At the Arber summit, a close snow cover is reported for 150–170 days yr^{-1} (Müller-Hohenstein 1973; Hauner 1980; Scheuerer 1997). In the sheltered cirques the snow melts considerably later than in more exposed locations. South of the Kleiner Arbersee (Seeloch) it persists until May or even June (Baumgartner 1970; Scheuerer 1997). For the age calculation an estimate of 30 cm snow cover for six months is assumed for the horizontal surfaces.

(iii) The Arber region is a densely forested area (Fig. 2). Several tree storeys occur and a moss and shrub cover grows on some bedrock surfaces. Some of the sampled surfaces were covered with a thin moss and humus layer. For the age calculation the mean of the reported biomass values of

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Fig. 2: Field photographs from the Bavarian Forest. Upper left is boulder BW-03-02, upper right is boulder BW-03-15, lower left shows the snow cover on top of boulders in the snow-rich winter of 2004, lower right shows the vegetation cover on some of the boulders. If the tree that is growing on the boulder falls over it is likely to topple the boulder (this boulder was not sampled).

Abb. 2: Geländeaufnahmen aus dem Bayerischen Wald. Oben links: Moränenblock BW-03-02, oben rechts: Moränenblock BW-03-15, unten links: Schneebedeckung auf einem Moränenblock im schneereichen Winter 2004, unten rechts: Vegetationsbedeckung auf Moränenblöcken. Wenn der Baum, der auf dem Moränenblock wächst, umfällt, wird der Block voraussichtlich gedreht (der Moränenblock wurde nicht beprobt).

spruce forests in Bavaria was assumed (360 t ha^{-1} for cultivated forests, Dietrich et al. 2002). This does neither comprises understorey vegetation nor humus cover. Forest cover of the study area is assumed for the last 10 ka. Radiocarbon dated pollen diagrams from the Kleiner Arbersee indicate that the first arboreal pollen occurred around 13.9–15.0 cal ka BP (12,311±372 ^{14}C yr BP; Raab 1999), indicating that the area was already forested around this time.

(iv) A (negative) vertical movement of the Bavarian Forest of 0 to -0.9 mm yr^{-1} has been measured (station Wettzell, T. Klügel, pers. comm. 2005). For the correction of the production rate calculation a value of -0.5 mm yr^{-1} was estimated for the exposure duration.

Alpine Foreland:

(i) The exposure ages were calculated using an erosion rate of 5.5±2 mm ka^{-1} based on field observations and measurements (appendix 1).

(ii) For snow cover corrections, the average snow depth (20 cm) and density (0.3 g cm^{-3}) for about 4 months per year as measured at a near-by site (Attmannspacher 1981) are used in the calculations.

Tab. 1: Exposure ages determined on moraines of the Kleiner Arbersee glacier, Bavarian Forest.

Tab. 1: Expositionsalter von Moränen des Kleiner Arbersee-Gletschers, Bayerischer Wald.

Sample ID	**Lat / Long**	**Altitude**	**Height above ground, base plane area**	**Sample thick-ness**	**f_{corr} (topo, slope)***	**f_{corr} (veg, snow)***	**f_{corr} (geo-mag)**	**^{10}Be atom†**	**AMS error**	**Production rate§**	**Apparent age#**	**Exposure age****
	[°]	[m asl]		[cm]				[g^{-1} SiO_2^{-1} *10^5]	[%]	[atm g^{-1} yr^{-1}]	[^{10}Be ka]	[^{10}Be ka]
WIa - moraine												
BW-03-15	49.13°N 13.12°E	862	1.1 m 4.6 m²	3.5	0.997	0.965	1	2.09	3.3	10.5	19,508	20.7±2.1 [±0.6]
BW-03-14	49.13°N 13.12°E	848	0.9 m 2.6 m²	4	0.997	0.964	1	1.83	6.8	10.2	17,379	18.4±2.1 [±1.1]
BW-03-16	49.13°N 13.12°E	874	1.4 m 13.2 m²	4	0.997	0.964	1	1.95	3.4	10.5	18,024	19.2±1.9 [±0.5]
WIb - moraine												
BW-03-06	49.13°N 13.12°E	873	1.3 m 10.5 m²	4.5	0.997	0.964	1	1.90	4.3	10.4	17,640	18.7±1.9 [±0.7]
BW-03-02	49.13°N 13.12°E	864	3 m	4.5	0.996	0.964	1	1.88	4.1	10.3	17,649	18.7±1.9 [±0.7]
WI lateral moraine before it splits into WIa and WIb												
BW-03-07	49.13°N 13.12°E	860	2 m 4.5 m²	4.5	0.995	0.963	1	1.69	4.5	10.3	15,951	16.9±1.8 [±0.7]
BW-03-08	49.13°N 13.12°E	936	1.3 m 5.3 m²	3.5	0.996	0.964	1	2.03	3.6	11.1	17,775	18.8±1.9 [±0.6]
BW-03-17	49.13°N 13.12°E	892	1.8 m 7.35 m²	5	0.997	0.962	0.99	1.63	7.5	10.5	14,973	15.9±1.9 [±1.0]
BW-03-18	49.13°N 13.12°E	893	0.9 m 5.2 m²	4.5	0.996	0.961	0.99	1.54	6.0	10.5	14,090	15.0±1.7 [±0.8]
BW-03-19	49.13°N 13.12°E	898	1.4 m 5.1 m²	4.5	0.994	0.963	1	1.79	3.5	10.6	16,396	17.4±1.8 [±0.5]
WII moraine												
BW-03-03	49.13°N 13.12°E	870	1.5 m 2.4 m²	4	0.996	0.963	0.99	1.76	4.0	10.4	16,364	17.4±1.8 [±0.6]
Bw-03-04	49.13°N 13.12°E	871	1.1 m 6 m²	6.1	0.996	0.961	0.99	1.53	4.9	10.2	14,472	15.4±1.7 [±0.6]
BW-03-20	49.13°N 13.12°E	870	1.2 m 1.4 m²	4.5	0.995	0.963	1	1.74	3.7	10.4	16,243	17.2±1.8 [±0.5]
Lake moraine												
BW-04-03	49.13°N 13.12°E	905	2 m 12 m²	3.5	0.996	0.962	1	1.66	4.5	10.7	14,894	15.8±1.7 [±0.6]
BW-04-04	49.13°N 13.12°E	915	3.2 m 10.5 m²	3.5	0.996	0.962	1	1.68	9.9	10.8	14,992	15.9±2.1 [±1.4]
BW-03-09	49.13°N 13.12°E	945	1.5 m 6.4 m²	4	0.997	0.961	0.99	1.61	4.1	11.0	14,092	15.0±1.6 [±0.5]
Bedrock surface south of lake												
KAS-1-1	49.13°N 13.12°E	935	bedrock	0.85-1	0.655	1.000	0.99	1.06	6	7.6	13,839	14.0±1.7 [±0.5]
KAS-2-1	49.13°N 13.12°E	935	bedrock	0.85-1	0.655	1.000	0.99	1.11	4.2	7.7	14,470	14.6±1.8 [±0.6]
KAS-3-1	49.13°N 13.12°E	935	bedrock	0.85-1	0.622	1.000	0.99	1.03	5.3	7.3	14,038	14.2±1.8 [±0.7]
Bedrock surface on summit (reference to this data in appendix)												
BW-04-01	49.11°N 13.13°N	1,350	bedrock	4.5	0.997	0.977	1	6.2 6.2	15.9	102.432 94.424	Erosion rate	Erosion rate

Note: Samples were processed and measured at ETH Zurich tandem facility. The ^{10}Be concentrations and exposure ages are based on AMS standard S555 with a nominal value of 95.5E-12 and an associated ^{10}Be half-life of 1.51 Ma.

* correction factor for the effect of topographic shielding and surface geometry (exponential depth profile, nucleonic attenuation length 155 g cm^{-2}, muonic attenuation length 1510 g cm^{-2}, coefficient m=2.3 for the nucleonic and m=2.1 for the muonic component).

† blank-corrected.

§ local production rate corrected for geometry, topography, sample thickness, erosion, snow cover, uplift and geomagnetic variations.

\# corrected only for topographic shielding, geometry and sample thickness.

** exposure age corrected for all mentioned factors (section 3), error give the 1-σ uncertainty including analytical and systematic errors to be used when quoting absolute exposure age of boulder; errors in parenthesis give only the analytical uncertainty for comparison of different boulders in the same area.

Tab. 2: Exposure ages determined on terminal moraine complex of the Isar-Loisach glacier, Alpine Foreland and from glacial deposits of the Inn glacier.
Tab. 2: Expositionsalter der Endmoränen des Isar-Loisach-Gletschers, Alpenvorland, und von glazialen Ablagerungen des Inn-Gletschers.

Sample ID	Lat / Long	Altitude	Height above ground, base plane area	Sample thickness	f_{corr} (topo, slope)*	f_{corr} (veg, snow)*	f_{corr} (geo-mag)	^{10}Be atom†	AMS error	Production rate§	Apparent age#	Exposure age**
	[°]	[m asl]		[cm]				[g^{-1} SiO_2^{-1} $*10^5$]	[%]	[atm g^{-1} yr^{-1}]	[^{10}Be ka]	[^{10}Be ka]
Maximum terminal moraine												
AVS-03-01	47.98°N 11.42°E	670	1.1 m 5.4m²	5.6	0.997	0.974	1.00	1.5	5.2	8.6	16,891	18.0±1.9 (±0.8)
AVS-03-05	47.99°N 11.40°E	645	1 m 11.2 m²	4.5	1	0.981	1.01	3.24	3.0	8.6	37,038	40.4±3.1 (±0.8)
AVS-03-06	47.99°N 11.40°E	650	1 m 3.6 m²	5	1	0.973	1.00	1.37	5.6	8.5	15,579	16.6±1.8 (±0.8)
AVS-03-10	48.02°N 11.40°E	650	1.1 m 5.9 m²	4.5	0.999	0.967	0.99	1.0	5.0	8.4	11,346	12.1±1.4 (±0.5)
AVS-03-11	48.02°N 11.40°E	655	1.1 m 4.2 m²	5	0.987	0.971	1.00	1.25	5.6	8.4	14,352	15.3±1.7 (±0.7)
AVS-03-22	47.99°N 11.40°E	685	1.2 m 4.5 m²	5.5	0.994	0.972	1.00	1.3	5.7	8.6	14,513	15.5±1.7 (±0.8)
Moraine arch ice-proximal to terminal moraine												
AVS-03-03	48.00°N 11.39°E	656	0.8 m 2.9 m²	5.5	0.997	0.974	1.00	1.47	4.5	8.5	16,661	17.9±1.9 (±0.7)
AVS-03-04	47.95°N 11.39°E	659	1 m 4.5 m²	4.5	0.996	0.972	1.00	1.29	7.9	8.5	14, 639	15.6±1.8 (±1.1)
Boulder inside the inner moraine arch												
AVS-03-09	48.00°N 11.38°E	625	2.7 m 8.4 m²	5.5	1	0.969	1.00	1.1	4.6	8.4	12,638	13.5±1.5 (±0.5)
Inn glacier - deposits												
AVC-04-01	47.81°N 11.93°E	495	2.5 m 80 m²	4.5	1	0.972	1.00	1.2	6.1	7.5	15,372	16.4±1.8 (±0.9)

Note: Samples were processed and measured at ETH Zurich tandem facility. The ^{10}Be concentrations and exposure ages are based on AMS standard S555 with a nominal value of 95.5E-12 and an associated ^{10}Be half-life of 1.51 Ma.
* correction factor for the effect of topographic shielding and surface geometry (exponential depth profile, nucleonic attenuation length 155 g cm^{-2}, muonic attenuation length 1510 g cm^{-2}, coefficient m=2.3 for the nucleonic and m=2.1 for the muonic component).
† blank-corrected.
§ local production rate corrected for geometry, topography, sample thickness, erosion, snow cover, uplift and geomagnetic variations.
\# corrected only for topographic shielding, geometry and sample thickness.
** exposure age corrected for all mentioned factors (section 3), error give the 1-σ uncertainty including analytical and systematic errors to be used when quoting absolute exposure age of boulder; errors in parenthesis give only the analytical uncertainty for comparison of different boulders in the same area.

(iii) The study area is presently covered by a closed forest. Corrections of the exposure ages for the effect of vegetation cover were calculated from biomass measurements from the Ebersberg forest, west of Munich (340 t ha^{-1}; data reported by Cannell 1982). A closed vegetation cover was reconstructed for the late glacial Allerød period from drill cores proximal of the Inn glacier moraines (Schmeidl 1971; Beug 1976). For the age calculations the duration of a vegetation cover is only assumed for the last 11 ka.

(iv) The Eastern Alpine foreland is subject to uplift movements; postglacial uplift rates for the Eastern Alps and the forelands are partly due to isostatic adjustment (Fiebig et al. 2004) and have been determined to be 1–2 mm a^{-1} (Höggerl 1989). For the correction of production rate changes due to uplift, 1 mm a^{-1} over the (apparent) exposure time is assumed in this study.

The exposure ages in the result chapters are given with the 1-σ uncertainty. For comparison and precision of the exposure ages among one another only the analytical uncertainties are given, whereas when the averaged exposure age of the moraines (landform age) are stated the total uncertainty including the analytical as well as the systematic uncertainties are given.

Radiocarbon ages were calibrated using the INTCAL09 curve (Reimer et al. 2009) and the online radiocarbon calibration program Oxcal 4.1 (https://c14.arch.ox.ac.uk/oxcal/OxCal.html) (Bronk Ramsey 2009).

3 Study site – small mountain glaciation in the Bavarian Forest

3.1 Regional setting and glaciation in the study area

The Bavarian Forest was repeatedly glaciated throughout the Pleistocene (Ergenzinger 1967; Hauner 1980, 1998; Jerz 1993; Pfaffl 1997) but is not glaciated at present. In the Bavarian Forest, glacial landforms have been recognized along the north to south-eastern slopes of the mountain ranges that rise above 1,300 m asl (Rathsburg 1928; Priehäusser 1930; Ergenzinger 1967; Hauner 1980). The most recent glaciation in the Bavarian Forest was restricted to cirques and small valley glaciers (Ergenzinger 1967; Hauner 1980, 1998; Jerz 1993).

The study area is located in the small catchment (2.8 km^2) of the Seebach River on the northern slopes of the Grosser Arber Mountain, the highest part of the Bavarian Forest (Fig. 3, 4). Three glaciers developed on the slopes of the Grosser Arber during glaciations; the largest of them was the Kleiner Arbersee glacier extending north into the Seebach catchment (Priehäusser 1927; Rathsburg 1930; Pfaffl 1988, 1989). The wide saddle between Grosser and Kleiner Arber served as ice accumulation area (Ergenzinger 1967; Pfaffl 2001). During its last advance, the Kleiner Arbersee glacier extended about 2.5 km north from the saddle with a maximum lateral extent of 800 m (Raab 1999). The glacier eroded a number of flat to slightly inclined cirques on the slopes of the valley head (Ergenzinger 1967; Manske 1989). The shallow lake depression of the Kleiner Arbersee was excavated by a former glacier tongue (e.g. Bucher 1999). Moraines were deposited along the valley sides and to the north of the lake (Fig. 3, 4).

3.2 Sampling sites

A series of distinct lateral moraine ridges are preserved in the study area that flatten out into subdued, arcuate terminal moraines and are morphologically recognizable as ramping steps along the slope. The lateral moraine ridges are 5–10 m high and covered with many large moraine boulders (with a height above ground of up to 4 m; Fig. 2, Tab. 1). Moraine ridges are distinct on the eastern side of the catchment. On the western side they fade out on top of bedrock on the steep slopes south of the lake (Fig. 3, 4). The terminal and lateral moraines deposited by the Kleiner Arbersee glacier consist of clast-rich sandy to silty, bouldery, massive diamictons (Raab & Völkel 2003).

The outermost lateral moraine WI (terminology after Raab 1999; Fig. 3, 4) splits into two moraine ridges at around 900 m asl. This double-crested lateral moraine turns west about 50 m further down the slope and forms a set of terminal moraines. The outer ridge WIa passes into a shallow terminal moraine approximately 600 m north of the lake shore; the inner ridge of the terminal moraine WIb forms the southern part of the set of terminal moraines about 500 m north of the lake.

A morphologically distinct (~5–10 m high) terminal moraine WII was deposited by the downwasting glacier proximal to the WI moraines, about 400 m north of the lake. The terminal moraine WII passes into a distinct lateral ridge on the eastern side of the catchment. Inside the moraine WII and north of the lake a hummocky relief with numerous kettle holes and a few shallow ridges persists.

Along the eastern slopes of the catchment and ice-proximal of the WI and WII lateral moraines, two lateral moraine ridges are morphologically distinguishable (WIII and WIV; Raab 1999). Both moraine ridges flatten out at the northern lake shore. A subdued ridge of glaciolacustrine sediments (Mahr 1998; Raab 1999) dams the lake to the north and is covered with large moraine boulders.

On the southern side of the lake, the valley of the Seebach is narrow and vertical bedrock cliffs are exposed on the western catchment side. The bedrock consists of jointed sillimanite-cordierite gneiss (Troll 1967a, b; Ott & Rohrmüller 1998). Glacial erosion occurred mainly along these joint planes (Rathsburg, 1928; Raab 1999). The bedrock outcrops show glacial striations on protruding quartz veins indicating glacial abrasion.

3.3 Sample description and results of surface exposure dating

In the study area a total of 16 samples were taken from moraine boulders and bedrock surfaces (Fig. 3, 4, Tab. 1). Furthermore, we took samples from three glacially polished quartz veins south of the lake (Kubik & Reuther 2007; Reuther 2007), however, only the ^{10}Be nuclide concentration of the three surface samples will be included in the following discussion.

Terminal and lateral moraines (WI)

Four samples were taken from moraine boulders on the crest of the outer lateral ridge WIa, two come from boulders on the inner ridge crest of the lateral-terminal moraine set WIb. Four samples were taken on the lateral moraine ridge WI just before it splits into the two ridges WIa and WIb.

The oldest exposure ages were measured in boulders located on the outer ridge WIa (20.7±0.6 ka; 19.2±0.5 ka; 18.4±1.1 ka). The boulders located on the inner ridge WIb yield exposure ages, which are identical and younger than those on the outer ridge (18.7±0.7 ka; 18.7±0.7 ka). Boulder BW-03-19 (17.4±0.5 ka) on the inner side of the moraine is located ice-proximal to the ridge and its exposure age gives the age of the downwasting of the glacier from the WI moraine.

The exposure ages measured from the boulders on the lateral moraine WI before it splits into WIa and WIb are more scattered. Boulder BW-03-18 (15.0±0.8 ka) on the lateral moraine WI is partially embedded in the proximal side of the moraine. It stands 0.9 m above the ground on its ice-proximal side and only 10 cm on its ice-distal side. The young age might indicate a persistent thin sediment cover and exhumation of the surface well after deposition of the boulder. Boulder BW-03-07 (16.9±0.7 ka) on the outer moraine WIa is a tall (2 m) boulder with a small basal plane area (4.5 m^2) that is slightly tilted down slope. The boulder might have slightly rotated, explaining the 'too young' exposure age in comparison to the adjacent boulders. No explanation for the comparatively young exposure age of the massive boulder BW-03-17 (15.9±1.0 ka) on the lateral moraine WI is obvious. The boulder might have been toppled or tilted when nearby trees or trees growing on top of the boulder tipped over (e.g. Cerling & Craig 1994).

In summary, the double crest indicates that the set of outermost terminal and lateral WI moraines has been deposited by two different glacial oscillations. The initial glacial advance occurred before 20.7±2.0 ka. The exposure ages show a stratigraphical order from the oldest boulder located on the outer crest (landform age 19.1±2.0 ka) to the possibly slightly younger boulders on the inner crest (landform age 18.7±1.8 ka).

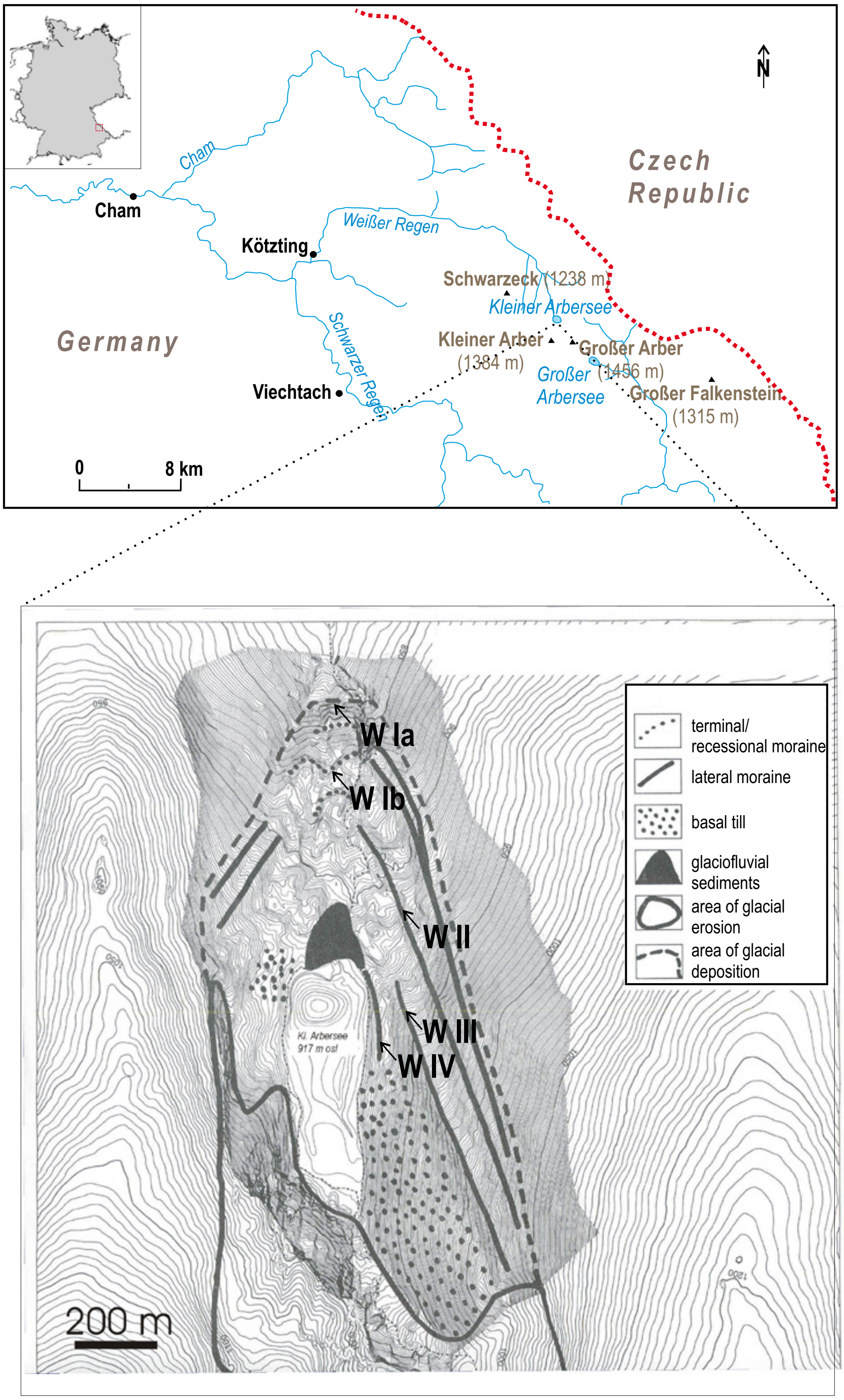

Fig. 3: Sketch map of Bavarian Forest and the location of the study area. Map of the glacial deposits around the Kleiner Arbersee from Raab *(1999).*

Abb. 3: Schematische Skizze des Bayerischen Waldes und Lage des Untersuchungsgebietes. Karte der glazialen Ablagerungen um den Kleinen Arbersee von Raab *(1999)*

Recessional/readvance moraine (WII)

Moraine WII is located only 100 m to the south of the terminal moraines. Two boulders right on top of the moraine crest (Fig. 3, 4) yield exposure ages of 17.4±0.6 ka and 17.2±0.5 ka. A third boulder (BW-03-04) on the same crest located between the two other boulders yields a much younger exposure age (15.4±0.6 ka). The boulder is massive and stands high above the surface. The young exposure age must be a result of either toppling of the boulder by a falling tree or spalling of the surface. The two well measured, identical exposure ages yield a landform age of 17.3±1.6 ka.

Lake moraine

Two samples were taken at the north-western end of the lake, where the lateral moraine ridges WIII and WIV fade out (Fig. 3, 4). The boulders are located on the end of the lateral moraines. One sample was taken from the ridge that dams the lake to the north (BW-04-03).

These three boulder surfaces yield exposure ages of 15.8±0.6 ka, 15.9±1.4 ka and 15.0±0.5 ka. The landform age of this moraine can be calculated to 15.7±1.7 ka with an arithmetic mean of the ages of 15.5 ka and a median of 15.7 ka.

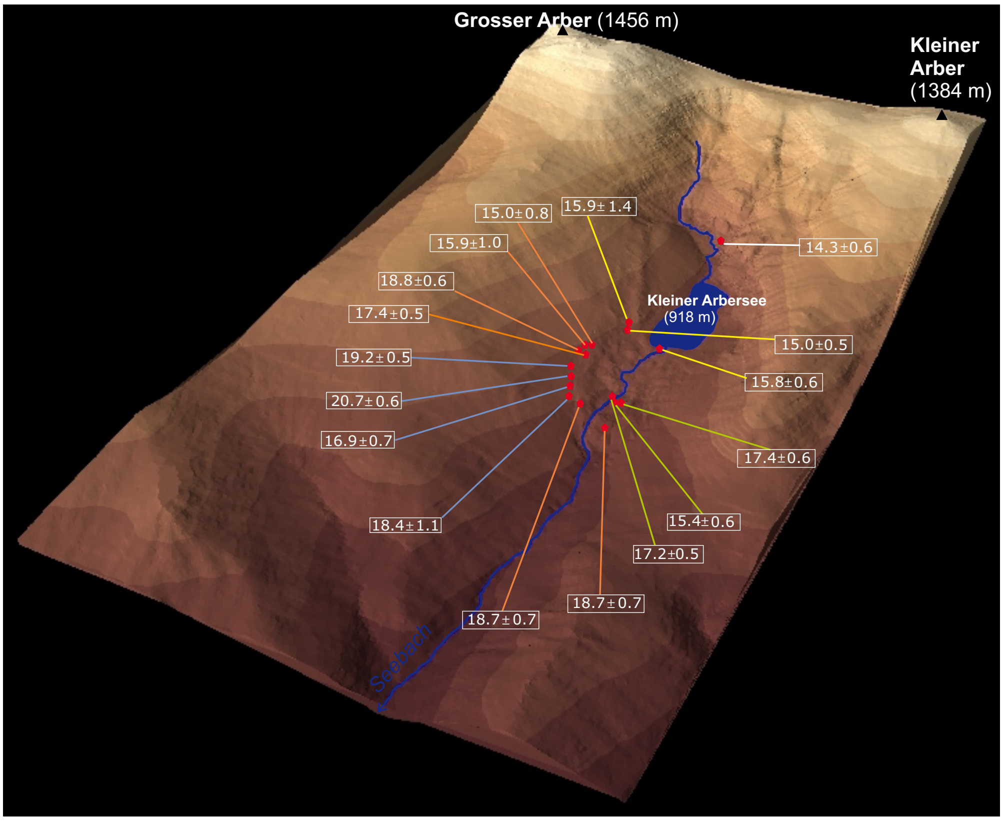

Fig. 4: Digital elevation model (DEM) of the study area in the Bavarian Forest, the location of the boulders and the respective exposure ages with the 1-σ analytical uncertainty. The moraines as well as the steep bedrock cliffs are well recognizable on the DEM.

Abb. 4: Digitales Geländemodell des Untersuchgebietes im Bayerischen Wald, Position der Moränenblöcke und den entsprechenden Expositionsaltern und Angabe der 1-σ Abweichung. Die Moränenzüge sowie die steilen Felsabbrüche sind im Geländemodell gut erkennbar.

Glacially polished quartz vein south of the Kleiner Arbersee

Samples were taken from a glacially polished quartz vein in a steep (70–80°) bedrock cliff south of the lake (KAS) 1.5 m above the ground surface. The outermost slices of the three bedrock cores (KAS-1-01, KAS-2-01, KAS-3-01) were dated to 14.3±1.8 ka (14.0±0.5 ka, 14.6±0.6 ka, 14.2±0.7 ka).

3.4 Discussion of results – Bavarian Forest

Moraine boulders on the late Würmian Kleiner Arbersee glacier yield stratigraphically consistent exposure ages. Boulders on the outermost moraine WIa give the oldest surface exposure ages, whereas moraine boulders on the proximal ridges become progressively younger. The consistency of the exposure ages documents the reliability of surface exposure dating in the study area and indicates that the exposure ages reflect the time of initial moraine stabilization after the glacier stopped delivering material onto the ridges. The well-preserved and distinct ridge morphology of the moraines indicates that thawing of dead ice bodies did not largely modify the moraines after deposition. In the study area a hummocky relief that might indicate the presence of dead ice after deglaciation is only present between the readvance moraine WII and the lake moraine, not on the moraines.

Deposition of the moraine boulders on the terminal moraines WI occurred no later than 20.7±2.0 ka. Moraine boulders on the outer ridge WIa were stabilized around 19.1±2.0 ka. Before 18.7±1.8 ka, the glacier melted back 50–100 m from its terminal position WIa and accumulated the inner ridge WIb, resulting in the double-ridge morphology of the terminal moraines. One could argue that the moraine boulder of 20.7±2.0 ka shows inherited nuclide abundance as the other boulders of the same moraine ridge cluster around 19.1±2.0 ka. However, the 20.7-ka boulder has a smooth and rounded surface indicating a rounding of the boulder and thus erosion prior to its deposition. Consequently, inheritance seems unlikely. Furthermore, the boulder is located on the outer shoulder of the terminal moraine ridge WIa, where stratigraphically the oldest boulders is to be expected.

The exposure age of boulder BW-03-19 suggests that the glacier melted back from the inner ridge of the moraine set WI at approximately 17.4±1.8 ka. The recessional moraine WII was deposited during an oscillation of the backwasting glacier at 17.3±1.6 ka.

The exposure ages from the two boulders on the lateral moraines at the northern lake shore and the boulder deposited on the arcuate ridge which dams the lake were deposited during a glacial readvance, around 15.7±1.7 ka. Deformed laminated glaciolacustrine sediments at the northern lake shore (Raab & Völkel 2003) are indicative of such a post-depositional readvance of the glacier.

As indicated by the exposure ages on the southern side of the lake, the glacier wasted back from the lake basin around 14.5±1.8 ka. These ages are in good accord with the radiocarbon ages that imply an ice-free lake basin no later than 13.9-15.0 cal ka BP (12,311±372 ^{14}C yr; Raab 1999) and with radiocarbon ages that indicate a backwasting of the Kleiner Arbersee glacier into the cirque locations by 12.5–12.9 cal ka BP (10,746±152 ^{14}C yr; Raab 1999).

The late Würmian chronology of the Kleiner Arbersee glacier indicates a deposition of the terminal moraines WI during a period of approximately 3,000 years and backwasting from its terminal moraines not before 17.4±1.8 ka. The melting of the glacier was therefore slow as compared to

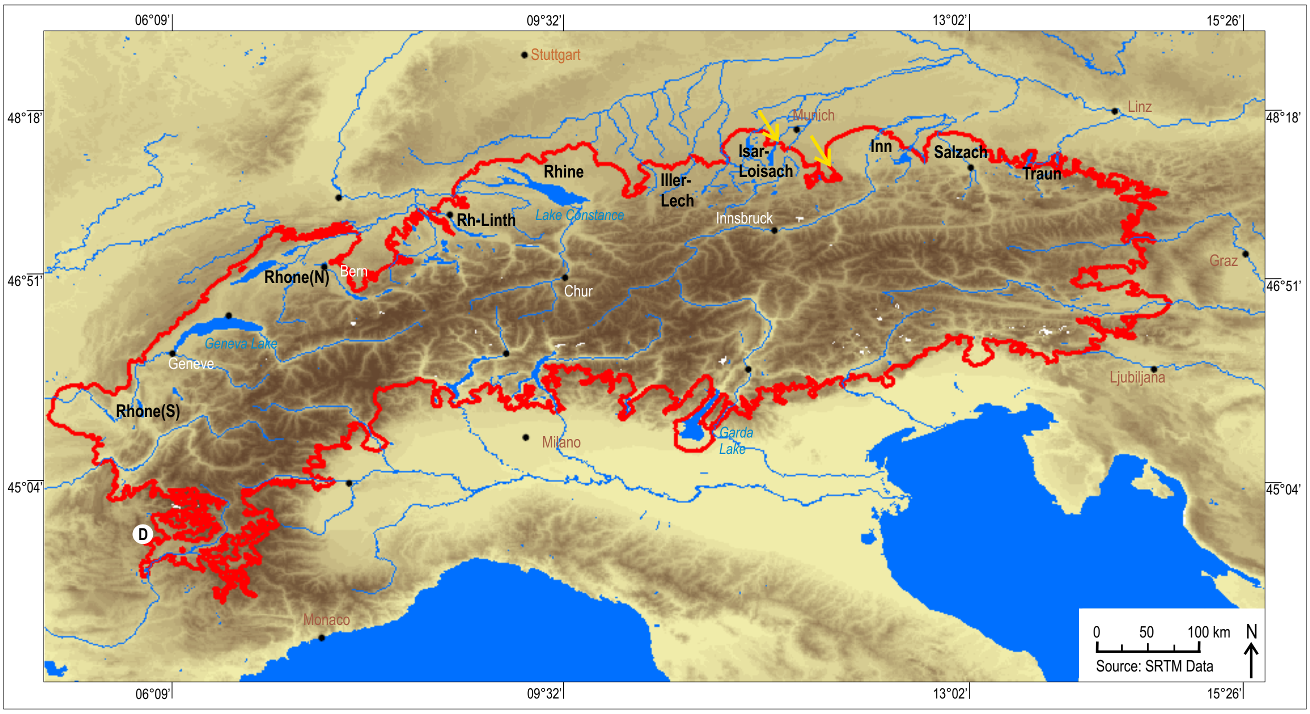

Fig. 5: Shaded relief of the Alps based on elevation data from the Shuttle Radar Topography Mission (SRTM). The red line marks the extent of the late Würmian Alpine ice cover (Ehlers & Gibbard 2004b), the yellow arrows mark the two sampling sites on the northern Alpine Foreland.

Abb. 5: Digitales Geländemodell der Alpen erstellt aus Daten der Shuttle Radar Topography Mission (SRTM). Die rote Linie beschreibt die spätwürmzeitliche alpinen Eisausdehnung (Ehlers & Gibbard 2004b), die gelben Pfeile markieren die Untersuchungsgebiete im nördlichen Alpenvorland.

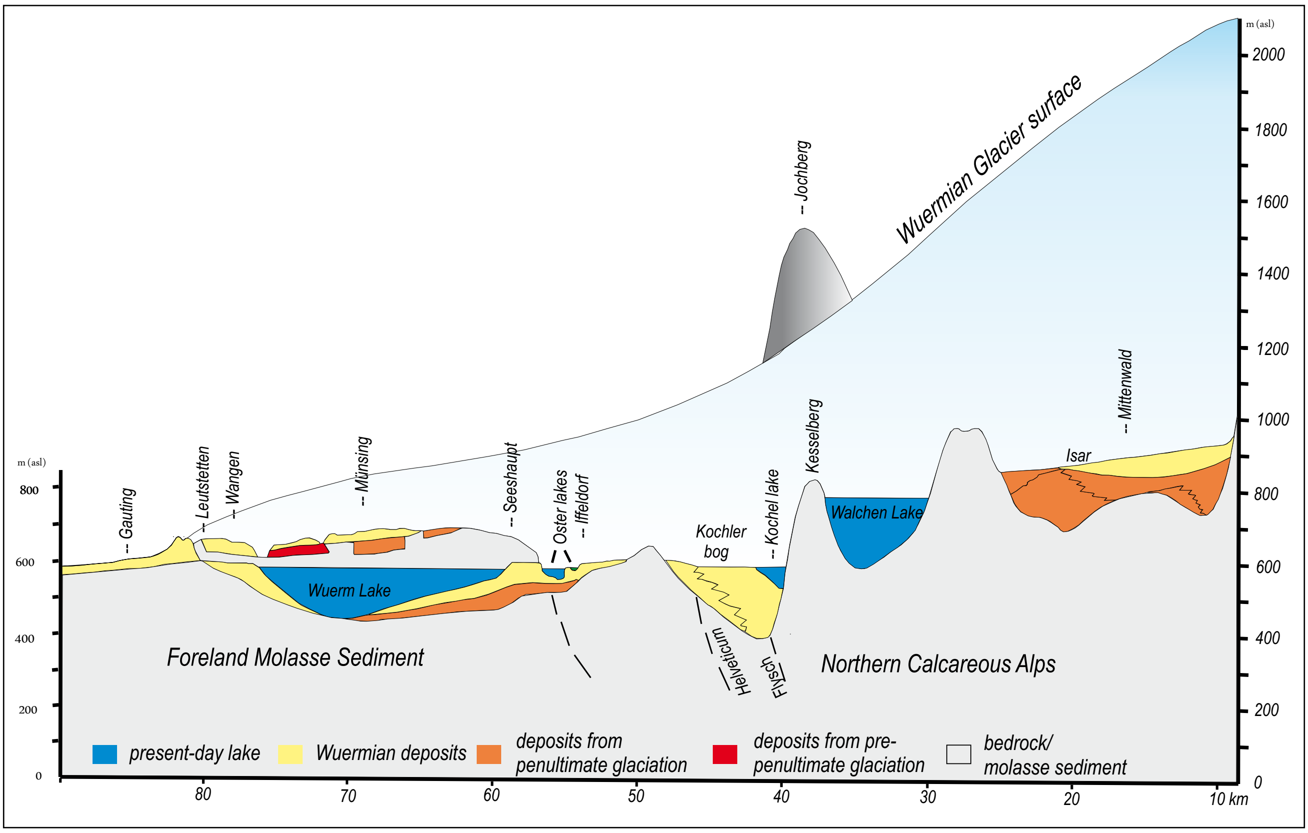

Fig. 6: Reconstructed ice surface of the Würmian piedmond lobe of the Isar-Loisach glacier with sketch of the the local geology (modified from Meyer & Schmidt-Kaler 1997, after map by van Husen 1987). A cross section through the Würmsee and the terminal moraines of the study area.

Abb. 6: Rekonstruierte Eisoberfläche des würmzeitlichen Piedmontlobus des Isar-Loisach Gletschers mit einer schematischen Darstellung der lokalen Geologie (abgewandelt von Meyer & Schmidt-Kaler 1997, nach einer Karte von van Husen 1987). Ein Querschnitt des Würmsees und den Endmoränen im Untersuchungsgebiet.

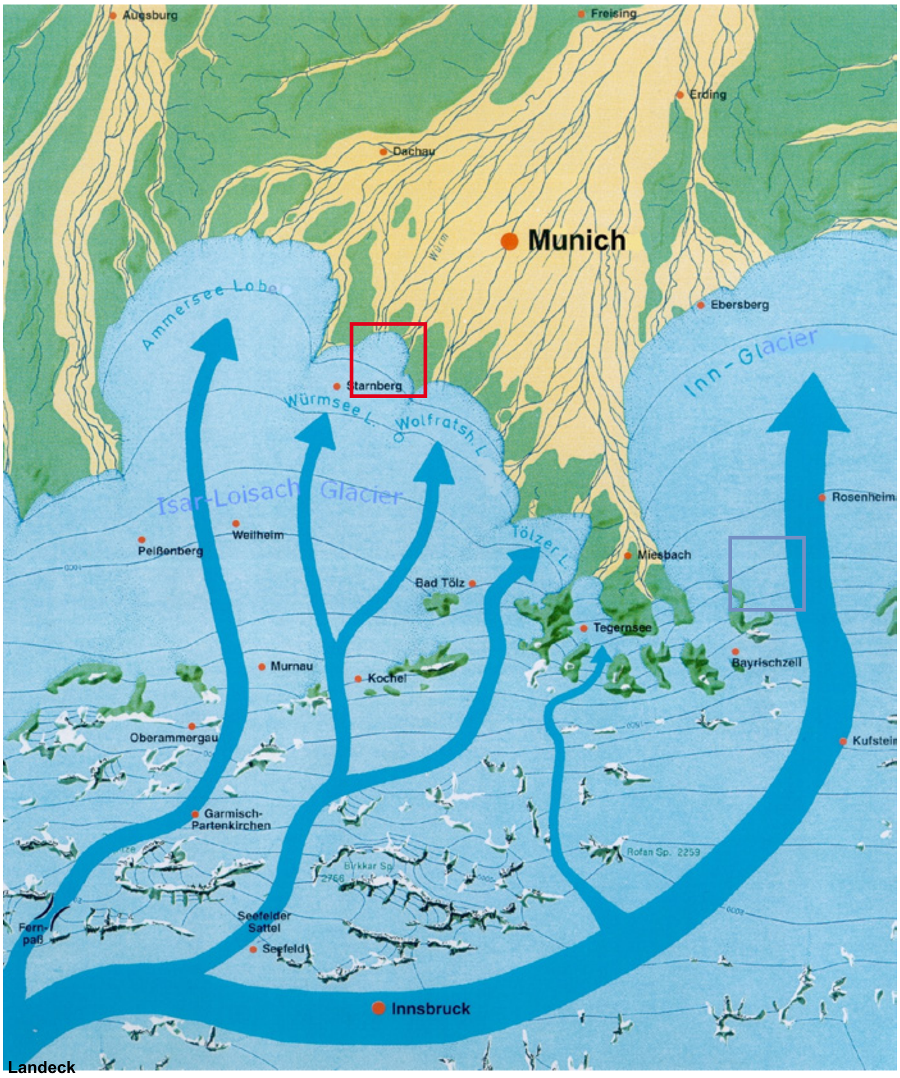

Fig. 7: Reconstructed late Würmian ice cover and the flow direction of ice streams that fed the Isar-Loisach and the Inn-glacier (modified from Meyer & Schmidt-Kaler 1997, after map by van Husen 1987). The squares mark the two sampling locations.

Abb. 7: Rekonstruierte Eisoberfläche des würmzeitlichen Eisbedeckung und Eisflußrichtung der Eisströme, die den Isar-Loisach und den Inngletscher gespeist haben (abgewandelt von Meyer & Schmidt-Kaler 1997, nach einer Karte von van Husen 1987). Die Vierecke markieren die Probennahmestellen.

the deglaciation in the Alps (see below). Melting back from the inner moraine ridge of the terminal moraine WIb, which stabilized around 18.7±1.8 ka, to the recessional moraine WII (horizontal distance about 120 m) took place over a period of about 1,400 years. Downwasting of the glacier from the recessional moraine WII into the lake basin (horizontal distance about 400 m) and the readvance to the lake moraine happened over about 2000 years.

4 Study site – large piedmont glaciers on Eastern Alpine Foreland

4.1 Regional setting and ice surface geometry

During Pleistocene glaciations, the high elevated central chain of the Eastern Alps was the main ice accumulation area for the Eastern Alpine glaciation (van Husen 1997). In different locations, such as the upper Inn valley, ice domes formed (Florineth & Schlüchter 1998; Florineth 1998). Furthermore, extensive glaciers accumulated on the high elevated plateaus of the Northern Calcareous Alps (van Husen 1997). During glaciations, the valleys were entirely filled with ice, and glaciers frequently overflowed passes (Beck 1932; Handtke 1980; Jäckli 1970; van Husen 1987). By reaching the limit of the Alps, the glaciers spread out as large piedmont lobes (Fig. 5). The glaciers excavated basins at the foothills of the Alps and large overdeepened basins on the forelands which were occupied by lakes following deglaciation (Fig. 6; Troll 1924; Frank 1979; Jerz 1987a, b; Kleinmann 1995; van Husen 2000). At present, the Eastern Alps are only glaciated at higher elevations, with an ELA around 2800–2900 m asl (Kerschner 1996).

The study area is the region of abandoned terminal moraines from the late Würmian Isar-Loisach glacier located south-west of Munich. A single exposure age was determined from deposits of the late Würmian piedmont lobe of the Inn glacier, south-east of Munich (Fig. 7).

The glacier complexes of the Inn and the Isar-Loisach glacier were tightly connected by ice transfluence (Fig. 7). During the late Würmian glaciation glaciers extending from the central Alpine ice accumulation areas merged around Landeck and build-up a thick ice mass in the Inn valley (van Husen 2000, 2004). The drainage through the Inn valley was already blocked by advancing tributary glaciers further down-valley. The ice congestion and increase in ice thickness resulted in an ice transfluence of the Inn valley ice to the north into the headwaters of the Isar and the Loisach (Fig. 7). The ice overflowed the divide in the Northern Calcareous Alps about 400–600 m above the bottom of the Inn valley (Penck 1882; Dreesbach 1985; Jerz

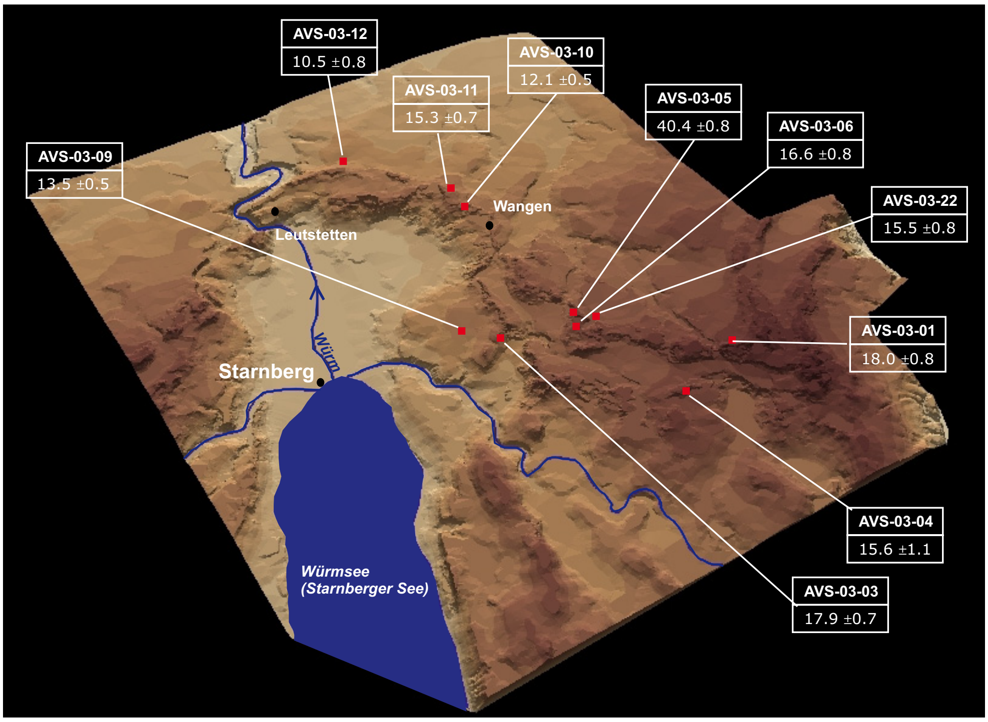

Fig. 8: DEM of the study area around the Würm Lake, the location of the sampled boulders and the respective exposure ages with the 1-σ analytical uncertainty. The DEM is based on contour lines from a 1:5,000 map and is 5-times vertically exaggerated. The arcuate moraines and the different ridges (see text) are well recognizable in the DEM.

Abb. 8: Digitales Geländemodell des Untersuchunggebietes um den Würm See, die Lage der beprobten Moränenblöcke und die entsprechenden Expositionsalter und Angabe der 1-σ Abweichung. Das Geländemodell basiert auf einer 1:5.000 Karte und 5-facher Überhöhung. Die gebogenen Moränenwälle und verschiedenen Moränenzüge (siehe Text) sind im Geländemodell auszumachen.

1993; van Husen 2000). The Isar-Loisach glacier itself had only a small local accumulation area in the Northern Alps. The large Isar-Loisach piedmont lobe extended about 60 km onto the forelands.

4.2 Glacial setting and sampling sites

The Würmian Isar-Loisach glacier deposited sets of arcuate terminal moraine ridges around the overdeepened lake basin of the Würmsee and the Ammersee (Fig. 8; Jerz 1979, 1993; Frank 1979; Feldmann 1992). During its initial late Würmian advance the Isar-Loisach glacier as well as the Inn glacier (Troll 1924; Gripp & Ebers 1957) deposited small moraines, only preserved in a few locations or diamictic layers without morphologically visible ridges (Jerz 1987a, b; Fiebig et al. 2004). These deposits are called the outer maximum or 'supermaximum' advance. High-prominent moraines a few tens to hundred meters south of the outer maximum moraines were referred to as the Würmian maximum moraines before the outer maximum extent was recognized. Based on field evidence, it is assumed that the glaciers melted back shortly after they reached their outer maximum position and subsequently deposited the high prominent 'maximum' moraine (Jerz 1993; Fiebig et al. 2004). Just proximal of the maximum late Würmian moraines, recessional and/or readvance moraines during deglaciation were deposited. In a few locations around the Würmsee, these ridges were pushed into one wide ridge (Fig. 8).
The ridges are in parts well-preserved but disrupted by numerous kettle holes, which today are filled with fens or seasonal kettle ponds (Engelschalk 1971; Grube 1983; Jerz 1987a, b). The steep-crested ridges are up to 40 m high and a couple hundred meters wide with locally flat tops (Grube 1983). The moraine ridges are broken up in multiple smaller ridges and small knolls. Meltwater channels frequently intersect the moraine ridges (Fig. 8; Jerz 1987a, b).

The Inn glacier spread out onto the foreland as a large piedmont lobe east of the Isar-Loisach glacier and excavated a large basin near the foothills of the Alps (Rosenheimer Becken). From this basin glacier lobes spread out radially (Fig. 7; Penck & Brückner 1901/09; Troll 1924; Hormann 1974; Rathjens 1985). The sequence of moraines and glacial deposits around the Inn glacier is very similar to that described for the former Isar-Loisach glacier (Troll 1924, 1925, 1957). The Isar-Loisach glacier advanced to its maximum extent later than the Inn glacier (Graul 1957).

Sample description and results of surface exposure dating
Nine erratic boulders were sampled from the terminal moraine complex of the Isar-Loisach glacier surrounding the Würmsee (Fig. 8, Tab. 2). No erratic boulders were found on the supermaximum position. One massive boulder was sampled on deposits from a late glacial glacier halt position of the Inn glacier.

Erratic boulders are rarely found on the moraine ridges on the Alpine foreland at present. The boulders are usually fairly small (1–1.5 m high; Fig. 9). All sampled boulders are of crystalline lithologies with a provenance in the Central Alps.

Six boulders were sampled on the maximum moraine ridge, whereas only two suitable boulders could be sampled on the first readvance and/or recessional moraine ridge. One sample was taken from a boulder just proximal of the inner moraine ridge (Fig. 8).

The measured exposure ages of the moraine boulders scatter from 40 ka to 14 ka. Three of the boulders are excluded from further interpretation as they are considered outliers. The six remaining boulders form a central age cluster with two older boulders and a tailing out of the age distribution towards the young. The ages range from 18.0±1.9 ka to 15.3±1.7 ka.

Out of the three outliers, two boulders (AVS-03-09, AVS-03-10) showed chipmarks at the sides of the boulder, whereas the sampled surfaces seemed untouched. They yield anomalous young ages (around 12–13 ka) that do not overlap within the 1-σ uncertainty with the age distribution of the other boulders. The boulder surfaces might have either been chipped without obvious evidence or the boulder might have toppled during the impacts. The third outlier (AVS-03-05) is a boulder with an anomalously old exposure age (around 40 ka) which we attribute to preexposure of the boulder and insufficient glacial erosion during the transport (inherited nuclide abundance), not an unusual phenomenon among moraine dating studies (Putkonen & Swanson, 2003).

The other moraine boulders show an overlapping age distribution. The oldest ages were obtained by boulder AVS-03-01 (18.0±1.9 ka) on the crest of the outer moraine ridge of the former Isar-Loisach glacier and by boulder AVS-03-03 (17.9±1.9 ka) on the crest of the inner moraine ridge (Fig. 8).

Boulder AVC-04-01 (16.4±1.8 ka) was sampled from glacial deposits of the late Würmian Inn glacier because it is the largest boulder found in the study area (Fig. 7, 9, Tab. 2). The boulder shows chipmarks on its west side, however, not on the surface. It is located on glacial deposits of the downwasting Inn glacier at the edge of the central Rosenheimer Becken, on a wide, not morphologically obvious rampart above the basin. This wide rampart might either represent a moraine ridge of the late glacial Ölkofener Stadium (Troll 1924; Jerz 1970a) or represent a till-covered, molasses-cored bedrock ridge (Troll 1924) in which case the boulder dates the downwasting of the Inn glacier.

4.3 Discussion of results – Eastern Alps

The moraine boulders on the terminal moraines of the Würmian Isar-Loisach glacier yield exposure ages that scatter from 18.0 ka±1.9 to 15.3±1.7 ka with an age cluster around 18 ka and a tailing out towards younger ages, falling well into the late Würmian. However, the distribution of boulder ages does not show a chronological order with respect to their location in the sense that ages are younger on the inner moraines (Fig. 8). The boulder situated on sediments of the downwasting Inn glacier yield an exposure age that is indistinguishable from ages determined on the terminal moraines of the Isar-Loisach glacier.

The timing of the maximum Würmian glacial extent in the Eastern Alps is bracketed by a few numerical ages from different locations throughout the Eastern Alpine that suggest a similar timing of the ice advance and deglaciation in the area (e.g. Furrer 1991; Schoeneich 1998; Preusser 2004; Ivy-Ochs et al. 2008; Kerschner et al. 2008). No numerical age has yet been derived from glacial deposits of the Isar-Loisach glacier. However, the ice-transfluence situation implies an ice-dynamic connection between the Isar-Loisach and the Inn glacier (Fig. 7). During deglaciation the Isar-Loisach glacier was cut off from its central alpine accumulation area by the time when the ice table in the Inn valley sank below the elevation of the ice transfluence. Therefore constraints on the timing of deglaciation of the Inn glacier yields broad information on the deglaciation of the Isar-Loisach glacier.

Published numerical chronologies suggest that the initial glacial advance of the Inn glacier in the late Würmian occurred around 25–33 cal ka BP as numerical ages from lacustrine sediments overlain by lodgement till in the Inn valley (30.3–33.0 cal ka BP [26,800 ± 1300 ^{14}C yr BP]; Fliri et al. 1970) and dated organic material in fluvioglacial deposits underlying Würmian till of the Inn glacier on the Alpine foreland (24.9–28.0 cal ka BP [21,900 +1230/ -1070 ^{14}C yr BP]; Habbe et al. 1996) suggest (Fig. 10). Following the peak of the maximum Würmian glaciation, the Inn glacier piedmont lobe disintegrated rapidly (Reitner 2005, 2007). A few radiocarbon ages on pollen bracket the late glacial vegetation history and thus put restraints on the climatic boundary conditions during deglaciation. An ice-free lower Inn valley around 17.4–16.8 cal ka BP (13,980±240 ^{14}C yr BP) is suggested by the basal age of a peat bog that developed about 300 m above the Inn valley near Innsbruck (Bortenschlager 1984a, b; Oeggl 1992). In tributaries of the Inn River, the late glacial Gschnitz advance was exposure dated to 15.5±1.8 ka (Ivy-Ochs et al. 2006a) and the Egesen (Younger Dryas) advance to 12.2±1.1 ka (Ivy-Ochs et al. 2006b). Similar ages were derived from the neighboring Rhein and Traun glaciers (e.g. Van Husen 1977; Geyh & Schreiner 1984; Preusser 2004).

In summary, numerical ages determined for the deglaciation of the Inn glacier show that the entire ice body had disintegrated and melted back into the Inn tributaries well before 16–15 cal ka BP by the time when a late glacial readvance of glaciers (= Gschnitz advance) in the tributaries occurred (Fig. 10).

The here presented exposure ages measured on the terminal moraines of the Isar-Loisach glacier, about 60 km north of the fringes of the Alps do not corroborate this independently derived chronology. However, as the exposure ages do not cluster tightly and are not internally coherent (Fig. 8), we suggest that the age distribution does not reflect the time of moraine deposition or abandoning of the moraine but rather the final moraine stabilization. Reasoning that the surface exposure ages measured here yield the true age of the moraine deposition would be in contradiction to all published numerical chronologies (see above) and field evidence for rapid deglaciation of Eastern Alpine glaciers (Reitner 2005, 2007; Ivy-Ochs et al. 2008).

The scatter in the measured exposure ages can be explained by periglacial surface processes or thawing of dead ice that exposed the boulder surface considerably after the boulder was deposited by the glacier (Fitzsimons 1996; Dyke & Savelle 2000; Everest & Bradwell 2003). Boulders embedded in the moraine matrix which are exhumed during moraine degradation processes document the time of landform stabilization rather than the moraine deposition time.

Thawing of dead ice and periglacial slope processes have affected the moraine morphology in the study area (Grube 1983) and the scatter in the age distribution presumably reflects the stabilization of the moraines. The described hummocky relief and the multiple kettle hollows in the moraines (Fig. 8, 11) suggest that following the deposition of the terminal moraines around the Würmsee the glacier melted down, separating dead ice bodies and leaving behind ice-cored moraines. Ice-contact sediments like kame terraces show that the downwasting Isar-Loisach glacier

Fig. 9: Field photographs from the Alpine Foreland. First picture depicts boulder AVS-03-01, second picture shows boulder AVS-03-22 and third picture shows the large erratic boulder from the Inn glacier deposits AVC-04-01.

Abb. 9: Geländeaufnahmen aus dem Alpenvorland. Das erste Photo zeigt den Moränenblock AVS-03-01, das zweite Bild den Block AVS-03-22 und das dritte Bild den großen erratischen Block von den Ablagerungen des Inngletschers AVC-04-01.

disconnected a large dead ice body that filled the lake basin of the Würmsee during deglaciation (Frank 1979; Bludau & Feldmann 1994; Kleinmann 1995; Feldmann 1998). The hummocky relief with many dead ice hollows and drumlin fields south of the Würmsee basin give further evidence for thawing of debris-covered dead ice complexes well after the initial deglaciation (e.g. Rothpletz 1917; Troll 1937; Bludau & Feldmann 1994).

Thawing of dead ice and periglacial slope processes on the moraines in the study area can explain, firstly, the large spread in exposure ages that tail out towards the young, secondly, the fact that the boulder ages do not reflect their geographic position with respect to the former ice margin (especially true for the age of the boulder from the Inn glacier deposits), and, thirdly, the fact that the two oldest boulders (AVS-03-01, AVS-03-03) are located right on top of well preserved ridges which were likely the first to stabilize. The younger boulders are located on moraine crests but are surrounded by a hummocky relief (Fig. 11).

There is ample evidence for periglacial conditions in the Alpine foreland during the late glacial such as the development of thick periglacial cover-beds and solifluction movement (e.g. Jerz 1970b; Semmel, 1973; Mailänder & Veit 2001; Bussemer 2002/03), evidence for dead ice bodies in the moraines (Grube 1983; Bussemer 2002/03), periglacially developed Buckelfluren (a special form of hummocky relief) (Jerz et al. 1966; Engelschalk 1971) and frost-wedges (Jerz et al. 1966; Menzies & Habbe 1992; Bussemer 2002/03).

The time period of the Eastern Alpine deglaciation was punctuated by different cold events which correlate with phases of colder sea surface temperatures in the North Atlantic (Heinrich-events; Bond et al. 1997). Von Grafenstein (1999) showed that these late glacial cold events are very well documented in the $\delta^{18}O_p$-record of the Ammersee in close proximity to the sampling sites on the Würmian moraines (Fig. 7). Furthermore, the late glacial Gschnitz advance (15.4±1.8 ka) in the Eastern Alps, that is tentatively correlated with H1, shows that the atmospherically transported ($\delta^{18}O_p$) cold pulses from the North Atlantic triggered glacial advances in the Alps (Ivy-Ochs et al. 2006a and references therein). Consequently, climatic conditions during H1 may have been favorable for periglacial activity on the Alpine foreland that could result in boulder exhumation by slope processes throughout the late glacial.

However, one could reason that there could be another explanation for the measured age distribution. One explanation for 'too young' exposure ages measured in erratics on the Alpine foreland moraines is quarrying of boulders by humans for which there is evidence since Neolithic times (e.g. Zehendner 1986), and is still ongoing today (gravestones, monuments). However, no obvious signs of quarrying were observed on the sampled boulder surfaces. Smooth boulder surfaces as well as protruding quartz veins indicate that no anthropogenic chipping occurred. Furthermore, the exposure ages of an extensively quarried boulder would be expected to be much younger than the observed ages or scatter considerably more.

Another explanation for the age distribution could be tilting or toppling of the boulders possibly caused by falling trees. Boulder movement can explain a large spread in ages and cause exposure ages being younger than the landform (Cerling & Craig 1994). However, toppling of boulders caused by trees is more likely to occur during the Holocene, when dense forests covered the study area. The absence of Holocene outliers renders this explanation of the age distribution unlikely.

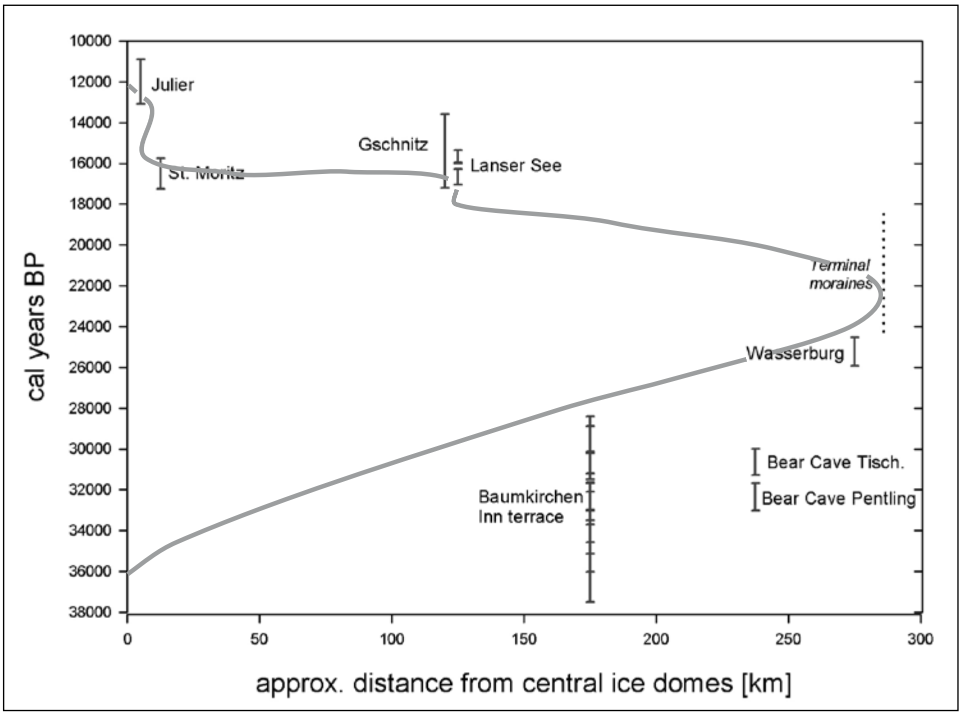

Fig. 10: Schematic time-distance diagram of ice-advance of the Inn glacier based on published radiocarbon, luminescence and exposure ages. The reported ages are taken from Kneussl *(1972, 1973),* Fliri *(1973),* Bortenschlager *et al. (1978),* Suter *(1981),* Bortenschlager *(1984a, b),* Habbe *et al. (1996),* Ivy-Ochs *et al. (2006a, b).*

Abb. 10: Schematisches Zeit-Entfernungsdiagramm der Eisvorstöße des Inngletschers basierend auf publizierten Radiokohlenstoff-, Lumineszenz- und Expositionsalterdatierungen. Die Alter stammen aus: Kneussl *(1972, 1973),* Fliri *(1973),* Bortenschlager *et al. (1978),* Suter *(1981),* Bortenschlager *(1984a, b),* Habbe *et al. (1996),* Ivy-Ochs *et al. (2006a, b).*

Chipping of the surface or toppling of boulders is not suited to convincingly explain the exposure age distribution measured in the study area. We therefore interpret the age distribution as indicative for a glacial environment with persistent dead ice in the moraines, periglacial slope processes that might have exhumed boulders until final moraine stabilization in the late glacial.

5 Discussion of results with respect to the two different glacial environments

We have presented and discussed the results of two new exposure dating studies in south-eastern Germany based on the profound work of Reuther (2007). Dating of moraine boulders of the maximum Würmian ice extent in two different glacial environments has shown that the age distributions determined in the two study areas are very different (Fig. 12) despite the similarity of the climatic boundary conditions.

A consistent and precise late Würmian chronostratigraphy was derived from moraines and bedrock surfaces in the catchment of a small valley glacier in the Bavarian Forest. Its initial ice advance occurred shortly before 20.7±2.0 ka. The glacier deposited two distinct lateral moraines in a time period of 2–3 ka of glacier oscillation around 18–19 ka. A first recessional moraine was deposited at 17.3±1.6 ka and a late glacial readvance occurred around 15.5±1.6 ka. The glacier melted back into its cirque location after 14.5±1.8 ka. The exposure ages are consistent with bracketing radiocarbon ages (Raab *&* Völkel 2003).

The exposure age distribution from terminal moraines of the Isar-Loisach and the Inn glacier indicate a moraine deposition well before 18.0±1.9 ka, and a phase of moraine stabilization throughout the late glacial as implied by an older age cluster around 18.0±1.9 ka and a spread toward younger ages. Late glacial readvances in the Eastern Alps occurred after the piedmont lobes and interconnected valley glaciers had melted back into the steep tributary valleys forming a dendritic valley glacier system (Reitner 2007). Two distinct late glacial readvances in the Eastern Alps were the Gschnitz advance (~H1 cold event) and the Egesen advance (~Younger Dryas cold event) of which moraines are only preserved in small to medium size catchments of the Eastern Alps (Ivy-Ochs et al. 2006a, b). Both glacial advances have been exposure dated by others; the Gschnitz advance to about 15.5±1.8 ka (Ivy-Ochs et al. 2006a) and the Egesen advance to about 12.2±1.1 ka (Ivy-Ochs et al. 2006b).

Our results show that both glacial systems reached their maximum Würmian ice extent during the late Würmian (marine isotope stage 2; Fig. 12), supporting our basic assumption that the general circulation and climatic pattern in the two study areas were similar. Despite the broad synchronicity, the response time to climatic fluctuations of a small valley glacier in comparison to the response time of an extensive ice cap and piedmont glacier system is very different; with the small valley glacier in the Bavarian Forest being more sensitive to climatic signals. The synchronicity of the late glacial readvance in the Bavarian Forest (lake moraine) and the Eastern Alps (Gschnitz advance) around 16–15 ka ago suggests that phases of colder climates around the North Atlantic lead to glacier advances of small valley glaciers of the Bavarian Forest at the same time as the small tributary valley glaciers of the Eastern Alps advanced. Consequently, we attribute the differences in the age distributions determined on the respective terminal moraines to geomorphic processes affecting moraine stabilization differently in the two glacial environments.

Moraines deposited by the small valley glacier in the Kleiner Arbersee catchment stabilized shortly after the glacier abandoned the moraines. The fast slope stabilization is portrayed by the precise and coherent exposure age distribution on the moraines. The moraine morphology shows no signs for thawing of dead ice, and the moraine boulders are too tall and massive (Tab. 1) for exhumation during post-

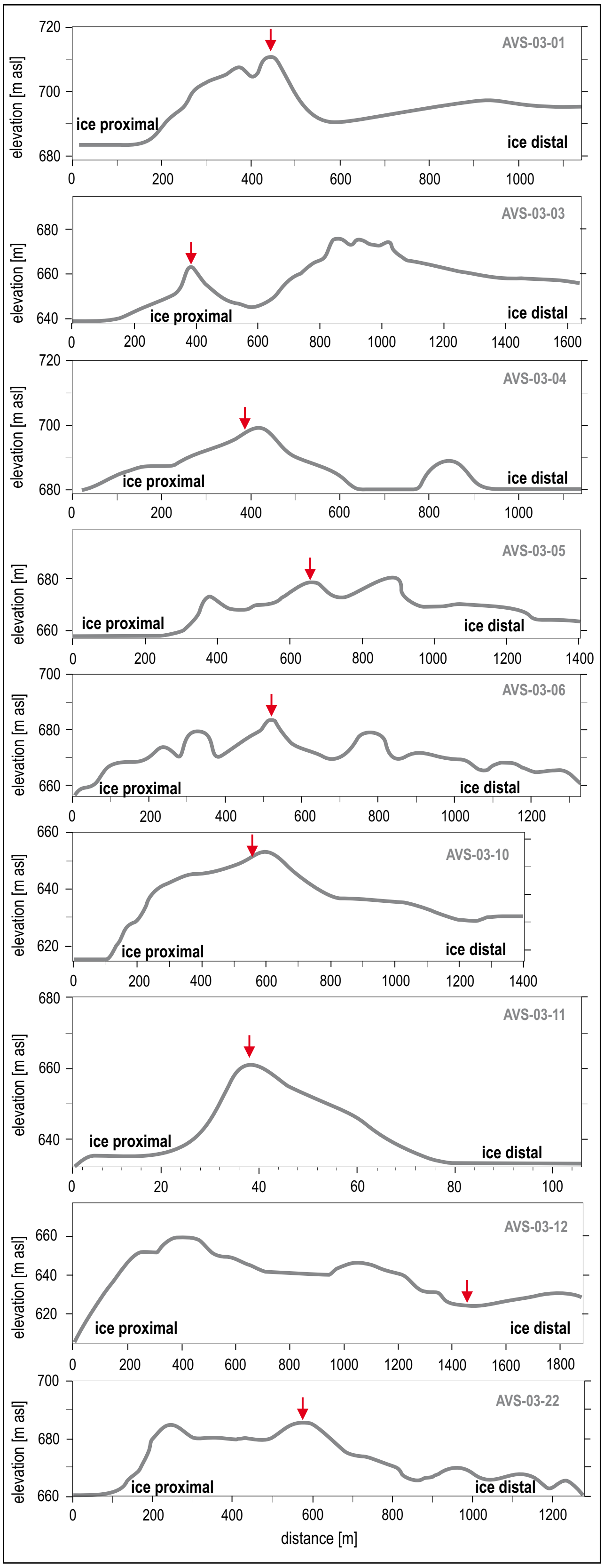

Fig. 11: Cross sections through the terminal moraine complex of the Isar-Loisach glacier at the sampling locations, showing the obvious hummocky relief and kettle holes. The red arrows mark the location of the sampled boulders. The cross sections cut the moraine wall radially. (Interpolated from the 1:5,000 contour line maps, 10x vertically exaggerated).

Abb. 11: Querschnitt durch den Endmoränenkomplex des Isar-Loisach Gletschers an den Probennahmestellen zeigen ein deutliches kuppiges Relief mit Toteislöchern. Der rote Pfeil markiert die Position des geprobten Findlings. Die Querschnitte schneiden die Moränen radial (Interpolation von 1:5.000 Höhenlinienkarten, 10fach vertikale Überhöhung).

depositional moraine degradation by periglacial slope processes. This relative landform stability is likely the reason for the coherent chronology.

In contrast, the surface topography of the moraines on the Alpine foreland (Fig. 8, 11) suggests that the landscape did not stabilize rapidly after the glaciers were cut off from their accumulation areas. Dead ice bodies likely prevailed until well after deglaciation of the region when periglacial activity ceased and the climate ameliorated. The age distribution measured in boulder surfaces from these moraines covers the entire late glacial. Moraine stabilization was not a function of the paleogeographic position, such as that the outer moraines stabilized first. The moraine boulders that yield the oldest ages are located on high moraine ridges with less evidence for thawing of dead ice, whereas the younger boulders are located on smaller ridges, surrounded by hummocky relief that implies delayed thawing of dead ice (e.g., Gripp & Ebers 1957). We therefore interpret the age distribution as indicative of a time period of melting of dead ice in the late glacial following the deposition of the set of terminal moraines. Furthermore, the boulders that were preserved on the moraines of the Alpine glaciers were relatively small in size (Tab. 2), some might have been exhumed after the initial moraine deposition during a phase of moraine degradation.

The deglaciation of the small valley glacier in the Bavarian Forest (2.5 km terminal moraine – cirque backwall) occurred by melting back of the glacier front at a slow and steady rate punctuated only by minor glacier oscillations. This slow melting reflects a rise of the glacial equilibrium line altitude (ELA) in the fairly steep Seebach valley under ameliorating climatic conditions in the late glacial. The readvance to the lake moraine occurred during a late glacial cold event, around the same time as the Gschnitz advance in the Alps.

In contrast, the rise of the ELA of the Eastern Alpine glaciers during deglaciation turned the piedmont lobes on the alpine foreland and in the low relief major valleys into stagnant ice masses (van Husen 1987). The nested terminal moraines of the maximum alpine ice advance were deposited by the large piedmont lobes extending over 200 km from the accumulation area to the north onto the flat foreland. The large ice masses did not react sensitively to short-lived climatic events. Only after they had melted back and formed separate valley glaciers during the late glacial, cold events are represented by moraines.

The two different data sets give insight into landscape stability and moraine degradation in different glacial environments and have important implications for sampling strategies for exposure dating studies on moraines.

Our results support preliminary studies that showed that precise exposure ages are not randomly distributed among moraines from all glacier types (Reuther et al. 2006). Small valley glaciers respond fairly rapidly to climatic changes and therefore a moraine can be deposited and stabilized in a short time period (~10^2 years). As a result moraines located in small alpine valleys with fairly simple moraine morphology may yield precise exposure ages (e.g. Gosse et al. 1995a, b; Ivy-Ochs et al. 1996, 1999; Owen et al. 2003; Vázquez-Selem & Heine 2004).

In contrast, piedmont ice lobes or ice sheets that extend

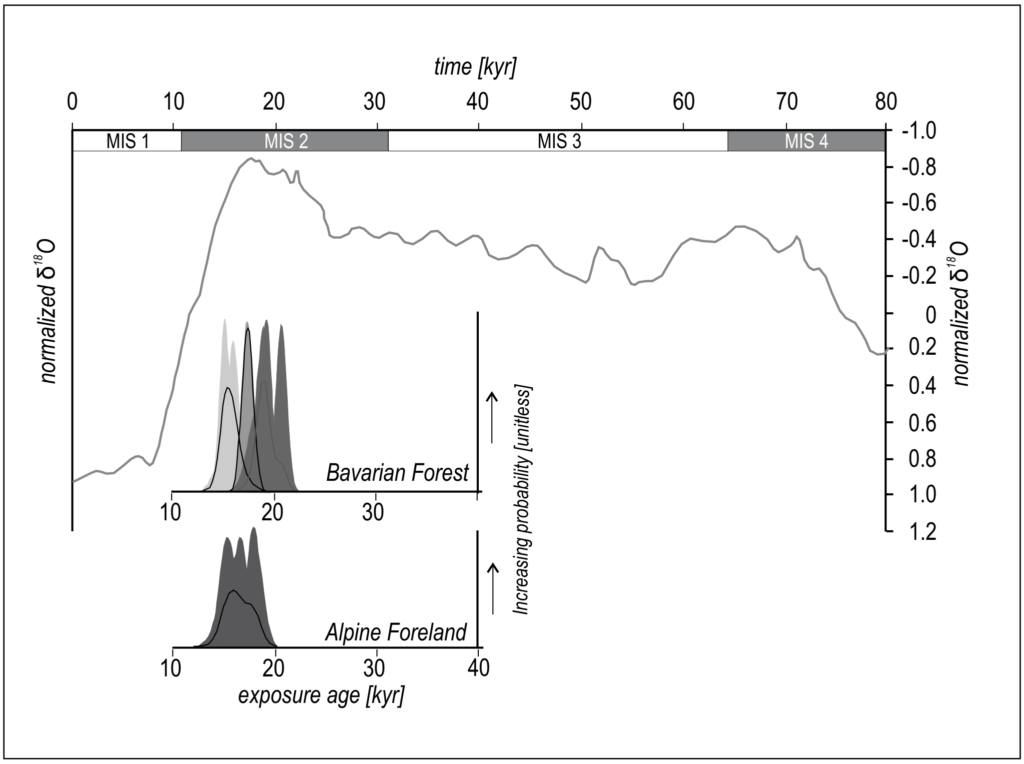

Fig. 12: Probability density diagrams of the exposure ages from the two study areas plotted against the $\delta^{18}O$ deep-sea North Atlantic Specmap curve (Martinson et al. 1987). The dark grey density functions show the outline of the exposure age distribution from all exposure ages measured on the respective terminal moraines in both study areas. The lighter grey age distribution outlines are from the ages measured on the recessional moraines in the Bavarian Forest. The solid dark line under the outline of the probability density functions (PDF) shows the sum of all PDFs from one moraine.

Abb. 12: Wahrscheinlichkeitsdichtediagramm der Expositionsalter der beiden Untersuchungsgebiete dargestellt gegen die $\delta^{18}O$-Tiefsee-Specmap-Kurven aus dem Nordatlantik (Martinson et al. 1987). Die dunkelgrauen Dichtefunktionen zeigen die Außenlinie der Expositionsalter-Verteilungen aller Alter, die auf den Endmoräne in beiden Untersuchungsgebieten gemessen wurden. Die hellgrauen Altersverteilungen zeigen die Alter, die auf den Rückzugsmoränen im Bayerischen Wald gemessen wurden. Die durchgezogene dunkle Linie beschreibt die Wahrscheinlichkeitsdichtefunktion der Summe aller Wahrscheinlichkeitsdichtefunktionen von den jeweiligen Moränen.

a few hundred kilometres from the accumulation area with a thickness of hundreds of meters will take much longer to arrive at equilibrium with the climatic conditions and may fluctuate for thousands of years around their maximum position and possibly disconnect large dead ice bodies (Gripp 1929; Owen et al. 2001; Benn & Owen 2002; Bowen et al. 2002). As a result, datasets from extensive piedmont lobe moraines with prominent (push-) moraines over wide foreland areas show considerably more scatter in ages (see above and also Ivy-Ochs et al. 2004) reflecting their more complex deglaciation history. Ice cored moraines will not stabilize before the melting of the ice core. Exposure dates of moraine boulders on moraine series deposited by an extensive piedmont lobe could give similar age ranges and the ages would have no geographical meaning in the sense of recessional moraines. Glacial deposits from large ice sheet margins similarly show some scatter in exposure ages (e.g. Licciardi et al. 2001; Balco et al. 2002; Bowen et al. 2002; Landvik et al. 2003; Rinterknecht et al. 2006). The only way to minimize the effect of exhumation of boulders during moraine stabilization is to sample tall and massive boulders.

Even though the described processes complicate data interpretation for moraine dating studies, this methodological challenge might open new avenues for determining phases of intensive slope processes on moraine and thawing of dead ice during which boulders were exhumed. Exposure dating in extra-glacial terrains has already been successfully used to constrain times of intensive periglacial activity in Australia (Barrows et al, 2004).

6 Summary and Outlook

The findings from this study can be grouped into three categories:

(1) Surface exposure ages from the catchment of the Kleiner Arbersee glacier yield a consistent and precise late Würmian local stratigraphy. The exposure ages are in agreement with the few published radiocarbon ages from the study area.

The initial glacial advance of the Kleiner Arbersee glacier occurred just before 20.7±2.0 ka. During the following 2–3 ka, the glacier deposited two distinct lateral moraines that form a set of terminal moraines. The outer ridge stabilized around 19.1±2.0 ka, the inner ridge stabilized at 18.7±1.9 ka. A first recessional moraine was deposited at 17.3±1.6 ka; a late glacial readvance occurred around 15.5±1.7 ka. The glacier melted back into its cirque location after 14.5±1.8 ka.

The exposure age distribution shows an insignificant scatter, so that precise moraine ages were derived, despite

E&G / Vol. 60 / No. 2–3 / 2011 / 248–269 / DOI 10.3285/eg.60.2-3.03 /

the dense forest cover in the study area. Even the deposition times of two ridges of a double-crested terminal moraine within 3 ka could be resolved. The moraines were not overprinted by post-depositional moraine degradation due to thawing of dead ice. This stability of the moraines is likely the reason for the precise exposure ages.

The local glacial chronology of the Kleiner Arbersee catchment indicates that the late Würmian glaciation was broadly synchronous with that of the Eastern Alps as implied by the late glacial advance around 16–15 ka. Consequently, the phases of 'glacier-friendly' climates during the late Würmian affected the small glaciers of the Bavarian Forest similarly as they affected the Eastern Alpine glaciers.

(2) Surface exposure ages from the type section of the Würm glaciation, the Würmsee area, show that maximum terminal moraines of the Isar-Loisach glacier and the Inn glacier were deposited during the late Würmian (MIS 2). The exposure ages, however, do not reflect the exact time of moraine deposition. Instead the age distribution, after exclusion of outliers, shows an older age cluster around 18 ka and a tailing out towards young ages. This age range is interpreted as indicative of a time of intensive moraine degradation due to melting of dead ice or periglacial slope processes that might have exhumed boulders from the moraine matrix during the late glacial (18–15 ka). There is ample independent evidence from the study area for intensive late glacial periglacial morphodynamic that could explain the slope processes from the terminal moraines on the Alpine foreland. The moraine boulders that yield the oldest ages are located on high moraine ridges, whereas the younger boulders are located on smaller ridges, surrounded by hummocky relief. The youngest boulder is located at the proximal side of the moraines in a former meltwater channel and was probably not exhumed before the end of the Pleistocene.

(3) The results of this study demonstrate again the great potential but also the pitfalls of surface exposure dating for establishing precise glacial chronologies from terrestrial records. Even though recent efforts have reduced the analytical and systematic errors of TCND, moraine ages often show more scatter than expected from the reported errors. The most important uncertainties in moraine dating are caused by geomorphological processes and thawing of dead ice.

The exposure ages from the two study areas prove that precise exposure ages are more likely determined from large boulders on well-preserved moraines, deposited by small valley glaciers. In contrast, the persistence of dead ice and prevailing of periglacial activity following deglaciation likely result in a post-depositional moraine degradation and exhumation of boulders resulting in exposure ages that scatter widely.

Moraine boulder ages do not only depend on the deposition of the landform but also on its erosion history. Landform degradation is considerable and operates on time scales that significantly interfere with the resolution of TCND that are routinely used to determine the ages of boulders on landforms comprised of unconsolidated materials. However, rates of moraine degradation are not uniform; they depend on the sedimentary composition of the moraine matrix material, the glacial environment, the presence of dead ice and on the climatic boundary conditions. Therefore, each data set and even each boulder exposure age has to be interpreted individually on the background of the relevant processes and the deposition environment. In any case the boulder age does not equate the age of the moraine, but the time of boulder stabilization.

Further refinement in moraine dating with TCND will only be possible if rates and timing of geomorphologic processes that result in moraine degradation can be better constrained.

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References

Attmannspacher, W. (ed.) (1981): 200 Jahre meteorologische Beobachtungen auf dem Hohenpeißenberg 1781–1980. – Berichte des Deutschen Wetterdienstes, 155: 84.

Balco, G., Stone, J. O., Porter, S. C. & Caffee, M. W. (2002): Cosmogenic-nuclide ages for New England costal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA. – Quaternary Science Reviews, 21: 2127–2135.

Barrows, T., Stone, J. & Fifield, L. K. (2004): Exposure ages for Pleistocene periglacial deposits in Australia. – Quaternary Science Reviews, 23: 697–708.

Baumgartner, A. (1970): Klima und Erholung im Bayerischen Wald. – In: Makowsky, H. & Weinzierl, H. (eds.): Natur, Freizeit und Erholung. Verhandlungen Deutscher Beauftragter für Naturschutz und Landschaftspflege, 17: 39–53.

Bayberger, F. (1886): Geographisch-geologische Studien aus dem Böhmerwalde. Die Spuren alter Gletscher, die Seen und Thäler des Böhmerwaldes. Petermann Geographische Mitteilungen 81. – 63 S.; Stuttgart (Klett).

Beck, P. (1932): Über den eiszeitlichen Aaregletscher und die Quartärchronologie. – Verein der Naturforschenden Gesellschaft Thun, 113: 343–359.

Benn, D. I. & Owen, L. A. (2002): Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains. - Quaternary International, 97–98: 3–25.

Beug, H. J. (1976): Die spätglaziale und frühpostglaziale Vegetationsgeschichte im Gebiet des ehemaligen Rosenheimer Sees, Oberbayern. – Botanische Jahrbücher für Systematik, Pflanzengeschichte und Pflanzengeographie, 95: 373–400.

Bludau, W. & Feldmann, L. (1994): Geologische, geomorphologische und pollenanalytische Untersuchungen zum Toteisproblem im Bereich der Osterseen südlich von Seeshaupt (Starnberger See). – Eiszeitalter und Gegenwart, 44: 114–128.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. & Bonani, G. (1997): A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. – Science, 278: 1257–1266.

Bortenschlager, S. (1984a): Die Vegetationsentwicklung im Spätglazial: Das Moor beim Lanser See III, ein Typprofil für die Ostalpen. – Dissertationae Botanicae, 72 (Festschrift Welten): 71–79.

Bortenschlager, S. (1984b): Die Beiträge zur Vegetationsgeschichte Tirols I. Inneres Ötztal und unteres Inntal. – Berichte des naturwissenschaftlich-medizinischen Vereins Innsbruck, Innsbruck, 71:19–56.

Bortenschlager, S., Fliri, F., Heuberger, H & Patzelt, G. (1978): Innsbrucker Raum und Ötztal. – Führer zur Tirol-Exkursion anlässlich der 19. wissenschaftlichen Tagung der Deutschen Quartärvereinigung 1978 in Wien. Innsbruck, 36 S.

Bowen, D. Q., Phillips, F. M., McCabe, A. M., Kuntz, P. C. & Sykes, G. A. (2002): New data for the Last Glacial Maximum in Great Britain and Ireland. – Quaternary Science Reviews, 21: 89–101.

Briner, J. P., Kaufman, D. S., Manley, W. F., Finkel, R. C. & Caffee, M. C. (2005): Cosmogenic exposure dating of late Pleistocene moraine stabilization in Alaska. – Geological Society of America Bulletin, 117: 1108–1120.

Bronk Ramsey, C. (2009): Bayesian analysis of radiocarbon dates. – Radiocarbon, 51(1), 337–360.

Bucher, M. (1999): Der glaziale Formenschatz im Gebiet um den Kleinen Arbersee (Bayerischer Wald, Deutschland). – Zeitschrift für Geomorphologie NF, Suppl.-Vol. 113: 45–58.

Bussemer, S. (2002/03):. Periglaziale Deckschichten und Bodenmosaike der Jungmoränenlandschaften von Oberbayern und Nordtirol. – Mitteilung der Geographischen Gesellschaft München, 86: 17–58.

Cannell, M. G. R. (1982): World forest biomass and primary production data. – 391 S.; London (Academic Press).

Cerling, T. E. & Craig, H. (1994): Geomorphology and in-situ cosmogenic isotopes. – Annual Reviews of Planetary Sciences, 22: 273–317.

Chaline, J. & Jerz, H. (1984): Arbeitsergebnisse der Subkommission für Europäische Quartärstratigraphie. Stratotypen des Würm-Glazials. – Eiszeitalter und Gegenwart, 35: 185–206.

Cockburn, H. & Summerfield, M. (2004): Geomorphological applications of cosmogenic isotope analysis. – Progress in Physical Geography, 28: 1–42.

Dietrich, H.-P., Raspe, S., Schwarzmeier, M. & Ilg, S. (2002): Biomasse- und Nährstoffinventuren zur Ermittlung von Ernteentzügen an drei bayerischen Fichtenstandorten. – In: Dietrich, H.-P., Raspe, S. & Preusler, T. (eds.): Inventur von Biomasse- und Nährstoffvorräten in Waldbeständen: 59–72; Forstliche Forschungsberichte, München (Wissenschaftszentrum Weihenstephan).

Dreesbach, R. (1985): Sedimentpetrographische Untersuchungen zur Stratigraphie des Würmglazials im Bereich des Isar-Loisach-Gletschers. – Dissertation, University of Munich, 176 S.

Dunne, J., Elmore, D. & Muzikar, P. (1999): Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth of sloped surfaces. – Geomorphology, 27: 3–11.

Dyke, A. S. & Savelle, J. M. (2000) : Major end moraines of Younger Dryas age on Wollaston Peninsula, Victoria Island, Canadian Arctic: implications for paleoclimate and for formation of hummocky-moraine. – Canadian Journal of Earth Sciences, 37: 601–619.

Ehlers, J. & Gibbard, P. L. (eds.), (2004a): Quaternary Glaciations – Extent and Chronology, Part I: 475 S.; Amsterdam (Elsevier).

Ehlers, J. & Gibbard, P. L. (eds.), (2004b): Quaternary Glaciations – Extent and Chronology, Part I: Digital data on CD; Amsterdam (Elsevier).

Ehlers, J., Eissmann, L., Lippstreu, L., Stephan, H. J. & Wansa, S. (2004): Pleistocene glaciations of Northern Germany. – In: Ehlers, J. & Gibbard, P. (eds.): Quaternary Glaciations – Extent and Chronology, Part I: 135–146; Amsterdam (Elsevier).

Engelschalk, W. (1971): Alpine Buckelfluren. – Regensburger Geographische Schriften 1: 159 S.; Regensburg (Institut für Geographie).

Ergenzinger, P. (1967): Die eiszeitliche Vergletscherung des Bayerischen Waldes. – Eiszeitalter und Gegenwart, 18: 152–168.

Evans, D. J. A. (ed.), (2004): Glacial landsystems. – 532 S.; London (Arnold).

Everest, J. & Bradwell, T. (2003): Buried glacier ice in southern Iceland and its wider significance. – Geomorphology, 52: 347–358.

Feldmann, L. (1992): Ehemalige Ammerseestände im Hoch- und Spätglazial des Würm. – Eiszeitalter und Gegenwart, 42: 52–61.

Feldmann, L. (1998): Der würmzeitliche Isar-Loisachgletscher. – GeoArchaeoRhein, 2: 103–120.

Fiebig, M., Buiter, S. J. H. & Ellwanger, D. (2004):. Pleistocene glaciations of South Germany. – In: Ehlers, J. & Gibbard, P. L., (eds.): Quaternary Glaciations – Extent and Chronology, Part I: 145-154; Amsterdam (Elsevier).

Fitzsimons, S. J. (1996): Paraglacial redistribution of glacial sediments in the Vestfold Hills, East Antarctica. – Geomorphology, 15: 93–108.

Fliri, F. (1973): Beiträge zur Geschichte der alpinen Würmvereisung: Forschungen am Bänderton von Baumkirchen (Inntal, Nordtirol). – Zeitschrift für Geomorphologie NF, Suppl.-Vol. 16: 1–14.

Florineth, D. & Schlüchter, C. (1998): Reconstructing the Last Glacial Maximum (LGM) ice surface geometry and flowlines in the Central Swiss Alps. – Eclogae Geologicae Helveticae, 91: 391–407.

Florineth, D. (1998): Surface geometry of the Last Glacial Maximum (LGM) in the southeastern Swiss Alps (Graubünden) and its paleoclimatological significance. – Eiszeitalter und Gegenwart, 48: 23–37.

Frank, H. (1979): Glazial übertiefte Täler im Bereich des Isar-Loisach-Gletschers. – Eiszeitalter und Gegenwart, 29: 77–99.

Furrer, G. (1991): 25.000 Jahre Gletschergeschichte dargestellt an einigen Beispielen aus den Schweizer Alpen. – Verein der Naturforschenden Gesellschaft Zürich Neujahrsblatt, 193, Zürich, 52 S.

Geyh, M. A. & Schreiner, A. (1984): ^{14}C-Datierungen an Knochen und Stoßzahn Fragmenten aus würmzeitlichen Ablagerungen im westlichen Rheingletschergebiet (Baden-Württemberg). – Eiszeitalter und Gegenwart, 34: 155–151.

Gosse, J. C. & Phillips, F. M. (2001): Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews, 20: 1475–1560.

Graul, H. (1957): Sind die Jungendmoränen im nördlichen Alpenvorland gleichaltrig? – Petermanns Geographische Mitteilungen Ergänzungsheft, 262 (Machatschek-Festschrift): 209–212.

Gosse, J. C., Evenson, E. B., Klein, J., Lawn, B. & Middleton, R. (1995b): Precise cosmogenic ^{10}Be measurements in western North America: Support for a global Younger Dryas cooling event. – Geology, 23: 877–880.

Gosse, J. C., Klein, J., Evenson, E. B., Lawn, B. & Middleton, R. (1995a): Beryllium-10 Dating of the duration and retreat of the Last Pinedale Glacial Sequence. – Science, 268: 1329–1333.

Gripp, K. (1929): Glaciologische und geologische Ergebnisse der Hamburgischen Spitzbergen Expedition 1927. – Abhandlungen des Naturwissenschaftlichen Vereins zu Hamburg, Hamburg, 249 S.

Gripp. K. & Ebers, E. (1957): Die Grenze von Inn- und Chiemseegletscher und die glazialmorphologische Kartenanalyse. – Petermanns Geographische Mitteilungen Ergänzungsheft, 262 (Machatschek-Festschrift): 227–239.

Grube, F. (1983): Morphologie der äußeren Würmvergletscherung in der Typusregion südlich München. – In: Führer zu den Exkursionen der Subkommission für Europäische Quartärstratigraphie vom 13.–20.09.1983. München: 13–16.

Habbe, K. A., Jerz, H. & Doppler, G. (1996): Schieferkohlen bei Wasserburg am Inn. - Exkursionsführer DEUQUA 15.–16.09.1996. Gmunden/Oberösterreich: 32 S.

Hallet, B. & Putkonen, J. (1994): Surface dating of dynamic landforms: Young boulders on aging moraines. – Science, 265: 937–940.

Hantke, R. (1980): Eiszeitalter. Die jüngste Erdgeschichte der Schweiz und ihrer Nachbargebiete. Band 2. – 703 S.; Thun (Ott).

Hauner, U. (1980): Untersuchungen zur klimagesteuerten tertiären und quartiären Morphogenese des Inneren Bayerischen Waldes, Rachel-Lusen, unter besonderer Berücksichtigung pleistozän kaltzeitlicher Formen. Nationalpark Bayerischer Wald. – Schriftenreihe Bayerisches Staatsministerium Ernährung, Landwirtschaft und Forsten, 6: 198 S.; München.

Hauner, U. (1998): „Geowissenschaftliche Projekte aus Ostbayern im Erdkundeunterricht" Projekt II: Pleistozäne Formen und Ablagerungen im Inneren Bayerischen Wald. – In: Hartl, M. & Huber, M. (eds.): Regensburg und Ostbayern mit Nachbarregionen – geographische Streifzüge: 94–99; München (Pfeil).

Heim, A. (1885): Handbuch der Gletscherkunde. – 560 S.; Stuttgart (Engelhorn).

Heine, K. (2011): Late Quaternary glaciations in Bolivia: Comments on some new approaches to dating morainic sequences. – In: Ehlers, J., Gibbard, P. & Hughes, P.D. (eds.): Quaternary Glaciations – Extent and Chronology, Part IV – A Closer Look: xxx-xxx; Amsterdam (Elsevier).

Heine, K., Reuther, A. U., Thieke, H. U., Schulz, R., Schlaak, N. & Kubik, P. W. (2009): Timing of Weichselian ice marginal positions in Brandenburg (northeastern Germany) using cosmogenic in situ ^{10}Be. – Zeitschrift für Geomorphologie N.F, 53: 433–454.

Höggerl, N. (1989): Rezente Höhenänderungen in Österreich abgeleitet aus Präzisionsnivellement-Messungen. – In: Lichtenegger H, Steinhauser P. & Sünkel H. (eds.): Tagungsbericht 5. Internationales Alpengravimetrie-Kolloquium Graz 1989, Österreichische Beiträge zur Meteorologie und Geophysik, 2:161–173.

Hormann, K. (1974): Ein neues Modell des würmzeitlichen Inn-Chiemsee-Gletschers – Überschiebungen des Inngletschers über den Tiroler Achengletscher bis in die Bereiche des heutigen Chiemsees. – Eiszeitalter und Gegenwart, 25: 35–47.

Ivy-Ochs, S. (1996): The dating of rocksurfaces in situ produced ^{10}Be, ^{26}Al and ^{36}Cl with examples from Antarctica and the Swiss Alps. – PhD Thesis No 11763, ETH Zürich, 196 S.

Ivy-Ochs, S., Kerschner, H., Kubik, P.W. & Schlüchter, C. (2006a): Glacier response in the European Alps to Heinrich event 1 cooling: the Gschnitz stadial. – Journal Quaternary Science, 21: 115–130.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Schäfer, J., Kubik, P. W., Maisch, M. & Schlüchter, C. (2006b): The timing of glaciations in the European Alps based on surface exposure dating with cosmogenic ^{10}Be, ^{26}Al, ^{36}Cl, and ^{21}Ne. - In: Siame, L. L., Bourles, D. L. & Brown, E. T. (eds.): In Situ Cosmogenic Nuclides and their Applications in Earth Sciences. Geological Society of America Special Paper, 415: 43–60.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W. & Schlüchter, C. (2008): Chronology of the last glacial cycle in the European Alps. – Journal Quaternary Science, 23: 559–573.

Ivy-Ochs, S., Schäfer, J., Kubik, P. W., Synal, H-A. & Schlüchter, C. (2004): Timing of deglaciation on the northern Alpine Foreland (Switzerland). – Eclogae Geologicae Helveticae, 97: 47–55.

Ivy-Ochs, S., Schlüchter, C., Kubik, P. W. & Denton, G. H. (1999): Moraine exposure dates imply synchronous Younger Dryas glacier advances in the European Alps and in the southern Alps of New Zealand. – Geografiska Annaler A, 81: 313–323.

Ivy-Ochs, S., Schlüchter, C., Kubik, P. W., Synal, H.-A. & Kerschner, H. (1996): The exposure age of an Egesen moraine at Julier Pass, Switzerland, measured with the cosmogenic radionuclides ^{10}Be, ^{26}Al and ^{36}Cl. – Eclogae Geologicae Helveticae, 89: 1049–1063.

Jäckli, A. (1970): Die Schweiz zur letzten Eiszeit: Atlas der Schweiz 6. Eidgenössische Landestopographie. Wabern-Bern.

Jerz, H. (1970a): Eisrandlagen und Oszillationen des würmzeitlichen Innvorlandgletschers. – Zeitschrift der Deutscben Geologischen Gesellschaft, 120: 13–22.

Jerz, H. (1970b): Zur Stratigraphie des Jungquartärs im nördlichen Alpenvorland nach ^{14}C-Datierungen. – Geologica Bavarica, 63: 207–216.

Jerz, H. (1979): Das Wolfratshausener Becken seine glaziale Anlage und Übertiefung. – Eiszeitalter und Gegenwart, 29: 63–69.

Jerz, H. (1987a): Erläuterungen zur Geologischen Karte von Bayern 1:25,000 zum Blatt Nr. 8034 Starnberg Süd: 173 S.; München (Bayerisches Geologisches Landesamt).

Jerz, H. (1987b): Erläuterungen zur Geologischen Karte von Bayern 1:25,000 zum Blatt Nr. 7934 Starnberg Nord: 128 S.; München (Bayerisches Geologisches Landesamt).

Jerz, H. (1993): Das Eiszeitalter in Bayern – Geologie von Bayern II. – 243 S.; Stuttgart (Schweizerbart).

Jerz, H. & Ulrich, R.(1983): Das Schieferkohlevorkommen von Herrnhausen südlich von Wolfratshausen. – Geologica Bavarica, 84: 101–106.

Jerz, H., Ulrich, R., Vidal, H. & Hohenstatter, E. (1966): Erläuterungen zur Geologischen Karte von Bayern 1:25 000, Blatt 8533/8633 Mittenwald: 152 S.+ map; München (Bayerisches Geologisches Landesamt).

Kelly, M. A., Buoncristiani, J.F. & Schlüchter, C. (2004): A reconstruction of the last glacial maximum (LGM) ice-surface geometry in the western Swiss Alps and contiguous Alpine regions in Italy and France. – Eclogae Geologicae Helveticae, 97: 57–75.

Kerschner, H. (1996): Multivariate statistical modelling of equilibrium line altitudes: Hintereisferner (Ötztal) – Stubacher Sonnblickkees (Hohe Tauern). – Zeitschrift für Gletscherkunde und Glazialgeologie, 32: 119–127.

Kerschner, H., Ivy-Ochs, S. & Schlüchter, C. (2008): Gletscher und Klima im Ostalpenraum zwischen 16.000 und 11.000 Jahren vor heute. – Abhandlungen der Geologischen Bundesanstalt, 62: 165–168.

Kleinmann, A. (1995): Seespiegelschwankungen am Ammersee. Ein Beitrag zur spät- und postglazialen Klimageschichte Bayerns. – Geologica Bavarica, 99: 253–367.

Kneussl, W. (1972): Vorbericht über eine Grabung in der Bärenhöhle am Pendling bei Kufstein (Nordtirol). – Zeitschrift für Gletscherkunde und Glazialgeologie, 8: 329–330.

Kneussl, W. (1973): Höhlenbärenknochen aus der Tischofer-Höhle (Kaisertal bei Kufstein – Nordtirol) mit ^{14}C-Methode altersbestimmt. – Zeitschrift für Gletscherkunde und Glazialgeologie, 9: 329–330.

Kohl, C. P. & Nishiizumi, K. (1992): Chemical isolation of quartz for measurement of in-situ-produced cosmogenic nuclides. – Geochimica et Cosmochimica Acta, 56: 3583–3587.

Kubik, P.W. & Reuther, A.U. (2007): Attenuation of cosmogenic ^{10}Be production in the first 20 cm below a rock surface. – Nuclear Instruments and Methods in Physical Research, Section B 259: 616–624.

Laj, C., Kissel, C. & Beer, J. (2004): High resolution global paleointensity stack since 75 kyr (GLOPIS-75) calibrated to absolute values. – Geophysical Monograph Series, American Geophysical Union, Washington D.C.: 255–265.

Lal, D. (1991): Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. – Earth Planetary Science Letters, 104: 424–439.

Landvik, J. Y., Brook, E. J., Gualtieri, L., Raisbeck, G., Salvigsen, O. & Yiou, F. (2003): Northwest Svalbard during the last glaciation: Ice-free areas existed. – Geology, 31: 905–908.

Licciardi, J. M., Clark, P. U., Brook, E. J., Pierce, K. L., Kurz, M. D., Elmore, D. & Sharma, P. (2001): Cosmogenic ^{3}He and ^{10}Be chronologies of the late Pinedale northern Yellowstone ice cap, Montana, USA. – Geology, 29: 1095–1098.

Mahr, A. (1998): Lockerbraunerden und periglaziale Hangsedimente im Bayerischen Wald. Untersuchungen zu Paläoumwelt und Geomorphodynamik im Spätglazial und ihrem Einfluß auf die Pedogenese. – Regensburger Geographisch Schriften, 30: 326 S.; Regensburg (Institut für Geographie).

Mailänder, R. & Veit, H. (2001): Periglacial cover-beds on the Swiss Plateau: indicators of soil, climate and landscape evolution during the Late Quaternary. – Catena, 45: 251–272.

Manske, D. (1989): Zur eiszeitlichen Überprägung des Arbergebietes, Bayerischer Wald. – Acta Albertina Ratisbonensia, 26: 183–198.

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C. & Shackleton, N. J. (1987): Age Dating and the Orbital Theory of the Ice Ages: Development of a High-Resolution 0 to 300,000-Year Chronostratigraphy. – Quaternary Research, 27: 1–29.

Menzies, J. & Habbe, K. A. (1992): A cryogenic wedge within gravels, north of Kempten, Bavaria, F.R.G. – Zeitschrift für Geomorphologie NF, 36: 365–374.

Meyer, R. K. F. & Schmidt-Kaler, H. (1997): Auf den Spuren der Eiszeit südlich von München, westlicher Teil. – Wanderungen in die Erdgeschichte 9. München: 126 S.

Müller-Hohenstein, K. (1973): Die naturräumlichen Einheiten auf Blatt 165/166 Cham. – In: Bundesforschungsanstalt für Landeskunde und Raumordnung (ed.): Naturräumliche Gliederung Deutschlands. Geographische Landesaufnahme 1:200,000. Bonn, 86 S.

Ochs, M. & Ivy-Ochs, S. (1997): The chemical behaviour of Be, Al, Fe, Ca, and Mg, during AMS target preparation from terrestrial silicates modeled with chemical speciation calculations. – Nuclear Instruments and Methods in Physical Research, Section B 123: 235–240.

Oeggl, K. (1992): Sediment- und Makrofossilanalysen aus dem Lanser See in Tirol, Österreich. Ein Beitrag zur spätglazialen Bio- und Chronostratigraphie der Ostalpen. – Flora, 186: 317–339.

Ott, W. D. & Rohrmüller, J. (1998): Geologische Karte von Bayern 1:25 000 Blatt 6944 Bodenmais. – München (Bayerisches Geologisches Landesamt).

Owen, L. A., Finkel, R. C., Minnich, R. A. & Perez, A. E. (2003): Extreme southwestern margin of late Quaternary glaciation in North America: Timing and controls. – Geology, 31: 729–732.

Owen, L. A., Gualteri, L., Finkel, R. C., Caffee, M. W., Benn, D. I. & Sharma, M. C. (2001): Cosmogenic radionuclide dating of glacial landforms in the Lahul Himalaya, northern India: defining the timing of Late Quaternary glaciation. – Journal of Quaternary Science, 16: 555–563.

Partsch, J. (1882): Die Gletscher der Vorzeit in den Karpathen und den Mittelgebirgen Deutschlands. – 198 S.; Breslau (Koebner).

Penck, A. & Brückner, E. (1901/09): Die Alpen im Eiszeitalter. – 1199 S.; Leipzig (Tauchnitz).

Penck, A. (1882): Die Vergletscherung der deutschen Alpen, ihre Ursachen, periodische Wiederkehr und ihr Einfluß auf die Bodengestaltung. – 484 S.; Leipzig (Barth).

Penck, A., Böhm, A. & Rodler, A. (1887): Bericht über eine gemeinsame Excursion in den Böhmerwald. – Zeitschrift der Deutschen Geologischen Gesellschaft, 39: 68–77.

Pfaffl, F. (1988): Glazialmorphologische Untersuchungen am Rachel-Nordkar und am Großen Arbersee im Bayerischen Wald. – Geologische Blätter Nordost Bayerns, 38: 7–26.

Pfaffl, F. (1989): Der Bayerische Wald im Tertiär und Quartär. – Geologische Blätter Nordost Bayerns, 39: 1–38.

Pfaffl, F. (1997): Zur Geologie des Arbergebietes. – In: Bayerisches Landesamt für Umweltschutz (ed.): Die Naturschutzgebiete am Arber. Schriftenreihe: Aus den Naturschutzgebieten Bayerns, 144: 9–14; München.

Pfaffl, F. (2001): Vor 30.000 Jahren: Gletscher am Arber. – Schöner Bayerischer Wald, 141: 35.

Phillips, F. M., Zreda, M. G., Smith, S. S., Elmore, D., Kubik, P. W. & Sharma, P. (1990): A cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, Eastern Sierra Nevada. – Science, 248: 1529–1532.

Preusser, F. (2004): Towards a chronology of the Late Pleistocene in the northern Alpine Foreland. – Boreas, 33: 195–210.

Priehäusser, G. (1927): Der Bayerische Wald im Eiszeitalter. I. Glaziale Spuren in der Umgebung des Großen Arbersees. – Geognostische Jahrhefte, 40: 133–150.

Priehäusser, G. (1930): Die Eiszeit im Bayerischen Wald. – Abhandlungen der Geologischen Landesuntersuchung des bayerischen Oberbergamtes München: 5–47.

Putkonen, J. & O'Neal, M. (2006): Degradation of unconsolidated Quaternary landforms in the western North America. – Geomorphology, 75: 408–419.

Putkonen, J. & Swanson, T. (2003): Accuracy of cosmogenic ages for moraines. – Quaternary Research, 59: 255–261.

Raab, T. (1999): Würmzeitliche Vergletscherung des Bayerischen Waldes im Arbergebiet. – Regensburger Geographische Schriften, 32: 327 S.; Regensburg (Institut für Geographie).

Raab, T. & Völkel, J. (2003): Late Pleistocene glaciation of the Kleiner Arbersee area in the Bavarian Forest, south Germany. – Quaternary Science Reviews, 22: 581–593.

Rathjens, C. (1985): Erläuterungen zur Geomorphologischen Karte 1:100 000 der Bundesrepublik Deutschland. GMK 100 Blatt 3, C8338 Rosenheim. GMK Schwerpunktprogramm: 69 S. + map; Stuttgart (GeoCenter).

Rathsburg, A. von (1928): Die Gletscher des Böhmerwaldes zur Eiszeit. – Berichte der Naturwissenschaftlichen Gesellschaft Chemnitz, 22: 65–161.

Rathsburg, A. von (1930): Neue Beiträge zur Vergletscherung des Böhmerwaldes während der Eiszeit. – Mitteilungen des Vereins für Erdkunde, Dresden, 106 S.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., McCormac, F. G., Manning, S. W., Reimer, R. W., Richards, D. A., Southon, J. R., Talamo, S., Turney, C. S. M., van der Plicht, J., & Weyhenmeyer, C. E. (2009). IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. – Radiocarbon, 51(4): 1111–1150.

Reinecker, J. & Lenhardt, W. A. (1999): Present-day stress field and deformation in eastern Austria. – International Journal of Earth Sciences, 88: 532–550.

Reitner, J. M. (2005): Quartärgeologie und Landschaftsentwicklung im Raum Kitzbühel – St. Johann i. T. Hopfgarten (Nordtirol) vom Riss bis in das Würm-Spätglazial (MIS 6-2). – Dissertation Univ. Wien, 190 S.

Reitner, J. M. (2007): Glacial dynamics at the beginning of Termination I in the Eastern Alps and its stratigraphic implications. – Quaternary International, 164/165: 64–84.

Reuther, A. U. (2007): Surface exposure dating of glacial deposits from the last glacial cycle. Evidence from the Eastern Alps, the Bavarian Forest, the Southern Carpathians and the Altai Mountains. – Relief – Boden – Paläoklima, 21, Schweizerbart, Stuttgart, 213 S. + Appendix A – E.

Reuther, A. U., Ivy-Ochs, S. & Heine, K. (2006): Application of surface exposure dating in glacial geomorphology and the interpretation of moraine ages. – Zeitschrift für Geomorphologie NF, Suppl.-Vol. 142: 335–359.

Rinterknecht, V. R., Clark, P. U., Raisbeck, G. M., Yiou, F., Bitinas, A., Brook, E. J., Marks, L., Zelčs, V., Lunkka, J.-P., Pavlovskaya, I. E., Piotrowski, J. A. & Raukas, A. (2006): The Last Deglaciation of the Southeastern Sector of the Scandinavian Ice Sheet. – Science, 311: 1449–1452 (and supporting online material).

Rother, K. (1995): Die eiszeitliche Vergletscherung der deutschen Mittelgebirge im Spiegel neuerer Forschungen. – Petermanns Geographische Mitteilungen, 139: 45–52.

Rothpletz, A. (1917): Die Osterseen und der Isar-Vorlandgletscher. – Mitteilungen der Geographischen Gesellschaft München, 12: 99–298.

Scheuerer, M. (1997): Das Klima des Arbergebietes. – In: Bayerisches Landesamt für Umweltschutz (ed.): Die Naturschutzgebiete am Arber. – Schriftenreihe: Aus den Naturschutzgebieten Bayerns, München, 144: 15–17.

Schmeidl, H. (1971): Ein Beitrag zur spätglazialen Vegetations- und Waldentwicklung im westlichen Salzachgletschergebiet. – Eiszeitalter und Gegenwart, 22: 110–126.

Schoeneich, P. (1998) : Corrélation du dernier maximum glaciaire et de la déglaciation alpine avec l'enregistrement isotopique du Groenland. – Bulletin d'Association Française d'Étude Quaternaire, 9: 203–215.

Semmel, A. (1973): Periglaziale Umlagerungszonen auf Moränen und Schotterterrassen der letzten Eiszeit im deutschen Alpenvorland. – Zeitschrift für Geomorphologie NF, Suppl.-Vol. 17: 118–132.

Seret, G., Dricot, E. & Wansard, G. (1990): Evidence for an early glacial maximum in the French Vosges during the last glacial cycle. – Nature, 346: 453–456.

Stone, J. O. (2000): Air pressure and cosmogenic isotope production. – Journal of Geophysical Research, 105 B10: 23753–23760.

Suter, J. (1981): Gletschergeschichte des Oberengadins: Untersuchung von Gletscherschwankungen in der Err-Julier-Gruppe. – Physische Geographie Universität Zürich, 2: 147 S.

Synal, H.-A., Bonani, G., Döbeli, M., Ender, R. M., Gartenmann, P., Kubik, P. W., Schnabel, C. & Suter M. (1997): Status report of the PSI/ETH AMS facility. – Nuclear Instruments and Methods in Physical Research, B123: 62–68.

Troll, C. (1924): Der diluviale Inn-Chiemsee-Gletscher. – 121 S.; Stuttgart (Engelhorn).

Troll, C. (1925): Die Rückzugsstadien der Würmeiszeit im nördlichen Vorland der Alpen. – Mitteilungen der Geographischen Gesellschaft München, 18: 281–292.

Troll, C. (1937): Die jungeiszeitlichen Ablagerungen des Loisachvorlandes in Oberbayern. – Geologische Rundschau, 28: 599–611.

Troll, C. (1957): Tiefenerosion, Seitenerosion und Akkumulation der Flüsse im fluvioglazialen und periglazialen Bereich. – Petermanns Geographische Mitteilungen, Ergänzungsheft 262 (Machatschek-Festschrift): 213–226.

Troll, G. (1967a): Bau und Bildungsgeschichte des Bayerischen Waldes. – In: Bayerisches Geologisches Landesamt (ed.): Führer zu geologisch-petrographischen Exkursion im Bayerischen Wald. – Geologica Bavarica, 58: 15–33.

Troll, G. (1967b): Der Arber-Kaitersberg Zug. – In: Bayerisches Geologisches Landesamt (ed.): Führer zu geologisch-petrographischen Exkursion im Bayerischen Wald. – Geologica Bavarica, 58: 53–66.

Van Husen, D. (1977): Zur Fazies und Stratigraphie der jungpleistozänen Ablagerungen im Trauntal. – Jahrbuch der Geologischen Bundesanstalt, Austria, 120: 1–130.

Van Husen, D. (1987): Die Ostalpen in den Eiszeiten. – 24 S. + 1 map; Wien (Geologische Bundesanstalt).

Van Husen, D. (1997): LGM and Late-Glacial fluctuations in the Eastern Alps. – Quaternary International, 38/39: 109–118.

Van Husen, D. (2000): Geological processes during the Quaternary. – Mitteilungen der Österreichischen Geologischen Gesellschaft, 92: 135–156.

Van Husen, D. (2004): Quaternary glaciations in Austria. - In: Ehlers, J. & Gibbard, P. L. (eds.): Quaternary Glaciations – Extent and Chronology, Part I: 1–13; Amsterdam (Elsevier).

Vázquez-Selem, L. & Heine, K. (2004): Late Quaternary Glaciation of Mexico. - In: Ehlers, J. & Gibbard, P. L. (eds.): Quaternary Glaciations – Extent and Chronology, Part III: 233–242; Amsterdam (Elsevier).

Von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J. & Johnson, S. J. (1999): A mid-European decadal isotope-climate record from 15,500 to 5,000 years BP. – Science, 284: 1654–1657.

Zech, R., Glaser, B., Sosin, P., Kubik, P.W. & Zech, W. (2005): Evidence for long-lasting landform surface instability on hummocky moraines in the Pamir Mountains, Tajikistan) from ^{10}Be surface exposure dating. – Earth and Planetary Science Letters, 237: 453–461.

Zehendner, M. (1986): Der Wald. – In: Fetzer, K. D. et al. (eds.): Standortliche Bodenkarte von Bayern 1: 50.000, München-Augburg und Umgebung: 91–100; München (Geologisches Landesamt).

Zreda, M. & Phillips, F. M. (1995): Insights into alpine moraine development from cosmogenic ^{36}Cl buildup dating. – Geomorphology, 14: 149–156.

Zreda, M., Phillips, F. M. & Elmore, D. (1994): Cosmogenic ^{36}Cl accumulation in unstable landforms. 2. Simulations and measurements on eroding moraines. – Water Resources Research, 30: 3127–3136.

Appendix

Erosion rates

1. Erosion rate determination in the study area Bavarian Forest

The local erosion rate of the cordierite-sillimanite gneiss in the study area of the Bavarian Forest was calculated from the measured nuclide concentrations at two different sites.

Protruding quartz veins along the vertical bedrock cliffs on the western catchment side are rounded at the sides and show striation in the direction of the former glacier flow. In order to confirm the glacial origin of these striae, instead of originating processes related to faulting of the jointed gneissic bedrock, a bedrock piece was investigated for recrystallization of minerals such as calcites typically found on fault-polish (Harnisch). No such forms were recognized (M. Keller, pers. comm. 2003), indicating that the quartz veins were actually glacially polished. Geomorphological field descriptions had already suggested a glacial origin of the striations (Rathsburg 1928, 1930). A minimum erosion rate of 3.1 mm ka^{-1} can be calculated from the surface relief of the protruding glacially polished quartz veins on the vertical cliff south of the lake (4.5 cm, KAS-1-1, 2-1, 3-1) and its apparent exposure age (14.6±1.8 ka). The erosion rate derived from the quartz veins in a steep wall is interpreted as a minimum erosion rate because the vertical wall has never been covered by organic material. Most of the other boulders in the study area, however, are covered by a humus-soil layer of varying thickness (see Fig. 2 main text). Surface weathering in the gneiss surfaces is considerably enhanced under the organic cover. Surfaces covered with soil showed loose chips of rock on the surface and the rock was more deeply weathered.

The relatively high nuclide concentration from a sampled surface on the Arber summit (BW-04-01) can be interpreted either as a minimum exposure age (98.4 ka, weighted mean of two measurements) when calculated without erosion, or as a maximum erosion rate. A maximum erosion rate is calculated if it is can be assumed that the nuclide concentration has reached a secular equilibrium state in which surface erosion and radioactive decay balances the production of nuclides in the surface. This allows one to solve the production equation for the long-term erosion rate of the bedrock. The high nuclide concentration in sample BW-04-01 may be indicative of the sample having reached secular equilibrium. The measured concentrations indicate an erosion rate of 5.7 mm ka^{-1} (weighted mean of the two measurements). This erosion rate constitutes a maximum erosion rate because a higher erosion rate would require the nuclide concentration in the surface to be lower. If the steady-state had not yet been reached, the calculated erosion rate would be too high.

As described above, a minimum erosion rate of 3.1 mm ka^{-1} and a maximum erosion rate of 5.7 mm ka^{-1} were derived in the study areas. Ivy-Ochs et al. (2006b) calculated a similar erosion rate from a weakly foliated granitic boulder in Switzerland (5.5 mm ka^{-1}).

An erosion rate of 5±2 mm ka^{-1} was assumed as a best estimate of the long-term erosion rate in the study area based on the calculated maximum and the minimum erosion rate.

2. Erosion rate determination in the study area Northern Alpine Foreland

Erosion of the surface of the boulders could be roughly estimated at boulder AVS-03-01, where a quartz vein was protruding approximately 5 cm above the rest of the surface. The quartz vein itself was not polished but had a rough surface, indicating that it is not the original surface. If an exposure age of the boulder of 16.5 ka is assumed, this surface relief suggests a minimum erosion rate of 3 mm ka^{-1}. Measurements of surface erosion rates in the Western Alps yield values of 3 mm ka^{-1} for a weakly-foliated hornblende granite at Solothurn from relief differences (Ivy-Ochs et al. 2004) and 5.5 mm ka^{-1} for a granitic boulder (Mont Blanc granite) at Montoz based on a saturation assumption (Ivy-Ochs et al. 2006b). In this study, an erosion rate of 5.5±2.5 mm ka^{-1} is used as an estimate for the age calculations.

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Casting new light on the chronology of the loess/paleosol sequences in Lower Austria

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Abstract: This paper presents a review on recently dated sections in well-known loess/paleosol sequences of Lower Austria. The dating results indicate that there was loess deposition during the Upper Würmian Pleniglacial as recorded in the profile Joching. However, most obtained ages are older than the Last Glacial Maximum (LGM) and therefore erosional processes, which led to the removal of younger deposits can be supposed.
Soil formation between ~28 ka and ~35 ka mainly resulted in the formation of Cryosols. Hence, in the studied profiles, there is no evidence for more intense interstadial pedogenesis during this time span. This might be of particular relevance to the stratigraphy of 'Stillfried B' (sensu Fink).
The 2nd age cluster lies between ~35 ka and ~57 ka i. e. the Middle Pleniglacial (Würmian) and is dominated by loess deposits intercalated with different Cryosols. This period is also characterized by colluvial processes.
There is a significant hiatus between ~57 ka and ~106 ka, a fact which might be due to long lasting and intensive erosional processes in the study areas. The oldest measured age of the Last Glacial is 106 ± 12 ka for the loess on top of 'Stillfried A' in Paudorf (Paudorfer Bodenbildung). Immediately below this pedocomplex and equivalents to it, ages of 124 ± 25 ka (Göttweig-Aigen), 159 ± 20 ka (Paudorf 1), and 170 ± 16 ka (Joching) were obtained in loess.
Furthermore, there is evidence for older Middle Pleistocene deposits in Stratzing, Paudorf 2, Göttweig-Furth and Langenlois.

(Löss-/Paläoboden Sequenzen in Niederösterreich im Licht neuer chronologischer Ergebnisse)

Kurzfassung: Der vorliegende Artikel gibt einen Überblick über neu datierte Abschnitte in bekannten Löss/Paläoboden-Sequenzen Niederösterreichs. Die Ergebnisse der Datierungen im Profil Joching deuten darauf hin, dass es im letzten Hochglazial zur Lösssedimentation kam. Die meisten erfassten Alter sind jedoch älter als das letzte Hochglazial, was auf Erosionsprozesse hindeutet, die zur Abtragung der jüngeren Lösse geführt hat.
In dem Abschnitt zwischen ~28 ka and ~35 ka wurden überwiegend Tundragleye gebildet. Eine intensivere interstadiale Bodenbildung ist nicht nachzuweisen. Dieses Ergebnis kann auch für die stratigraphische Einstufung von ‚Stillfried B' (sensu Fink) von Bedeutung sein.
Der folgende chronologische Abschnitt liegt zwischen ~35 ka and ~57 ka in Lösssedimenten mit eingeschalteten Tundragleyen. Auch dieser Abschnitt ist durch Umlagerungsprozesse charakterisiert.
Im Zeitraum von ~57 ka bis ~106 ka befindet sich eine markante Zeitlücke, die vermutlich auf langandauernde und intensive Erosionsprozesse im Untersuchungsgebiet zurückzuführen ist.
Die älteste Datierung in den Sedimenten des letzten Glazials mit 106 ± 12 ka befindet sich in Paudorf direkt über dem ‚Stillfried A'- Komplex (Paudorfer Bodenbildung). Direkt unter diesem Pedokomplex, bzw. vergleichbaren Pedokomplexen treten in Lössablagerungen Alter von 124 ± 2 5 ka (Göttweig-Aigen), 159 ± 20 ka (Paudorf 1), and 170 ± 16 ka (Joching) auf.
Darüber hinausgehende Alter konnten in Stratzing, Paudorf 2, Göttweig-Furth und Langenlois nachgewiesen werden.

Keywords: *Loess, Lower Austria, Luminescence dating, Paudorf, Joching, Göttweig, Stratzing, Langenlois*

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1 Introduction

Loess landscapes are widespread in Lower Austria. Especially the loess region adjacent to the eastern margin of the Bohemian Massif comprises famous loess sequences at Krems, Stratzing, Göttweig and Paudorf (Fig. 1). Equally important is the loess/paleosol sequence of Stillfried, which is situated further to the east.

Both regions have received much attention due to its archeological finds (e. g. Antl-Weiser 1997; Einwögerer et al. 2006; Händel et al. 2008; Neugebauer-Maresch 2008).

However, the well-developed loess/paleosol sequences in Lower Austria have not experienced much attention besides archeological investigations since the works of Fink (1956, 1976, and 1978). Since the 1930's (Götzinger 1936) attempts have been made to develop a common stratigraphy

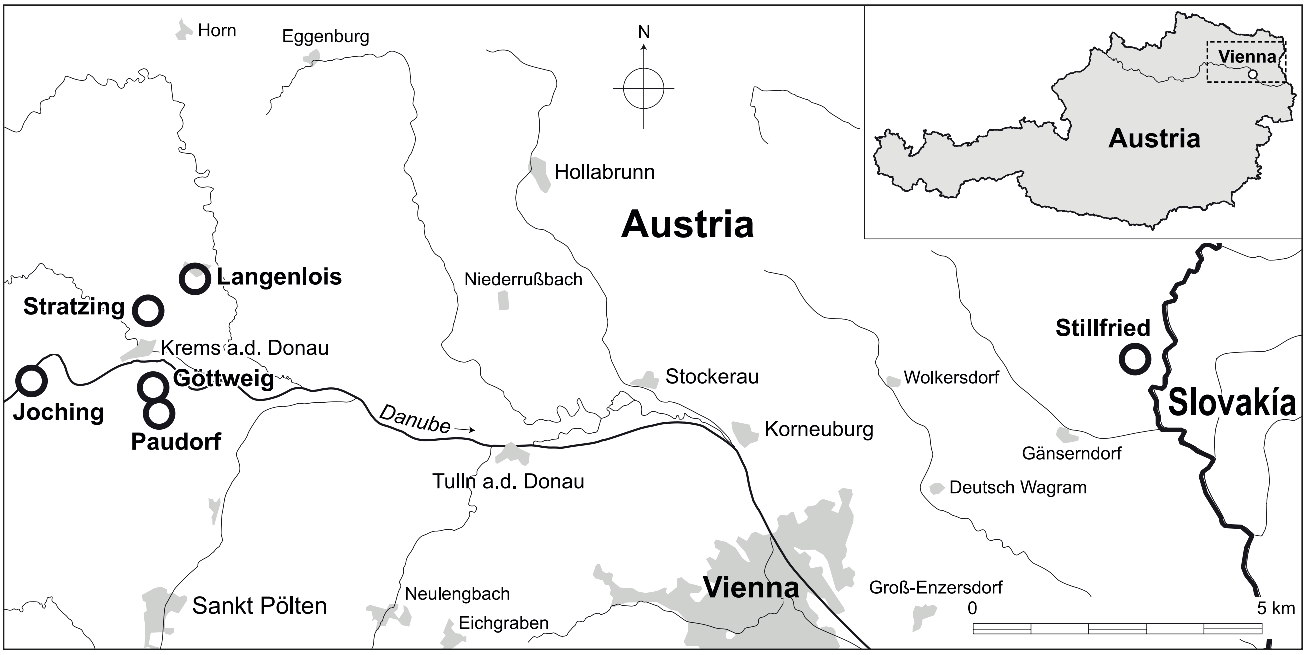

Fig. 1. Study sites in Lower Austria.

Abb. 1. Lage der untersuchten Profile in Niederösterreich.

for loess deposits in the area under study. This has not only been hampered by the lack of continuous records preserved but also by the lack of suitable dating techniques. Thus the chronological positions of many marker horizons such as the Stillfried complex (e.g. Fink 1976), the 'Göttweiger Verlehmungszone' and the 'Paudorfer Bodenbildung' (e.g. Götzinger 1936; Fink 1976) have caused much controversy (e. g. Noll et al. 1994; Zöller et al. 1994). Until then it was not certain which of these pedocomplexes depicts the last interglacial soil (Eemian). Due to enhanced dating techniques Thiel et al. (2011a) were able to clearly identify the 'Paudorfer Bodenbildung' at its type locality in Paudorf as the Eemian soil (Fig. 1). The 'Göttweiger Verlehmungszone' can most likely be attributed to the marine isotope stage (MIS) 11 or any older interglacial (Thiel et al. 2011b). However, these results have only been a small step towards the reconstruction of the former landscape in Lower Austria and its evolution. Other approaches to gain more information on pedogenesis and paleoenvironmental conditions in Lower Austria during the Quaternary have included micromorphological (e.g. Havlíček et al. 1998; Smolíková 2003; Smolíková & Havlíček 2007), geochemical (Haslinger & Heinrich 2008; Haslinger et al. 2009) and paleontological investigations (e.g. Frank & Rabeder 1997; Döppes & Rabeder 1997; Frank 1997; Fladerer et al. 2005). Due to topographically controlled variability of soil formation, the micromorpholocial attributes might not be sufficient to allow for stratigraphic correlations and numerical datings can complete the chronostratigraphy essentially.

Because Lower Austria is a geographical key position for the correlation of the dry loess landscape with the loess/paleosol sequences of east and south-east Europe, it is of great relevance to derive more information on loess deposition and paleopedogenesis as well as on erosion processes in time and space.

As an outline of current investigations in Lower Austria, this study presents first chronological results in form of short summaries from the study sites in Stratzing, Joching, Stillfried, Paudorf, Göttweig, and Langenlois (Fig. 1). Detailed profile description, analytical results, and luminescence dating details have been published elsewhere (Peticzka et al. 2010; Thiel et al. 2011a; b; c; 2011).

2 The chronological framework of the loess/paleosol sequences

2.1 Stratzing

The Stratzing loess/paleosol sequence (340 m a.s.l.) is situated at the eastern margin of the west-east elongated hill of the 'Galgenberg', which represents a characteristic landform in the loess area of the Kremser Feld (Fig. 1).

The loess/paleosol sequence of the Stratzing tennis court is exposed to a depth of 7.5 m and is subdivided in 19 units (Fig. 2: 1). Single thermoluminescence ages exist earlier from Zöller et al. (1994), detailed archeological investigations were conducted by Neugebauer-Maresch (1993) in nearby excavations, and malacological results were presented by Niederhuber (1997).

The basal part of the profile shows Middle Pleistocene loess deposits with an interglacial soil complex (ST18 and 19). The pedocomplex is covered by two loess layers (ST17) and a soil sediment (ST 16), which truncated the upper loess layer. Horizon ST 15 is the oldest archeological layer on top of which an alternating sequence of Cryosols and loess is visible (ST 14 to ST 6). This sequence exhibits two further archeological horizons (ST 13 and ST 10).

The uppermost part of the sequence consists of a loess layer (ST 5) and a well developed 1.0 m thick Cryosol pedocomplex (ST 4). The three uppermost horizons (ST 1–ST 3) are essentially disturbed by viticulture activities and are not described here.

Luminescence dating was applied to nine horizons (Thiel et al. 2011a; see Table 1). Making use of a post-IR IRSL dating protocol, the loess below the pedocomplex ST 18 and ST 19 and also its overlying loess (ST 17) were dated to > 300 ka (Thiel et al. 2011a). The colluvial layer (ST 16) indicates a hiatus, which is verified by an age of 117 ± 8 ka for horizon ST 15. Thiel et al. (2011a) considered the obtained age as an overestimate due to post-depositional mixing. Both, the colluvial layer and the luminescence dating result imply a great discontinuity in the sequence. The sediment deposition of layer ST 14 was dated to 57 ± 4 ka, and dating of ST 11 resulted in an age of 35 ± 2 ka. The age of cultural layer I (ST 10, sample 1627) was estimated to 32 ± 2 ka; this is in good agreement with the radiocarbon ages (cluster) obtained for this cultural layer from a neighbouring outcrop (Neugebauer-Maresch 1993; see discussion in Thiel et al. 2011a). For the loess layer (ST 5) a post-IR IRSL age of 31 ± 2 ka was obtained, and the overlying Cryosol complex (ST 4b) was dated to 28 ± 2 ka.

Highly fragmented fossil horse remains have been saved from the basal parts of the sequence. They belong to both mandibles, two vertebrae, and the metatarsal III of the right body side. The measurements combined with the tooth morphology allow to identify the finds as *Equus* cf. *mosbachensis*, which is a strong signal of Middle Pleistocene age.

2.2 Joching

The study site is located on the left bank of the Danube valley in the Wachau, about 15 km west to the city of Krems, Lower Austria (Fig. 1). The valley is deeply incised in Paleozoic bedrock of the Bohemian Massif, the overlying Middle Miocene sediments, and its slopes are partly covered by loess and intercalated paleosols. The most famous site of the area is the archeological excavation of Willendorf. There, the loess and loess-like sediments are of Middle to Upper Pleistocene age, with uncalibrated ^{14}C ages rang-

Tab. 1: Compilation of the recently published ages on the base of luminescence and ^{14}C-dating (Stillfried).

Tab. 1: Zusammenstellung der vor Kurzem publizierten Alter der Lumineszenz- und ^{14}C-Datierungen (Stillfried).

Site	Unit	Sample ID	Age (ka)
Stratzing[a]	ST4b	1625	28 ± 2
	ST5	1626	31 ± 2
	ST10	1627	32 ± 2
	ST11	1628	35 ± 2
	ST14	1629	57 ± 4
	ST15	1630	117 ± 8
	ST17b	1631	> 300
	ST19c	1632	> 300
	ST19d	1633	> 300
Joching[b]	J1	1398	16 ± 2
	J3	1399	47 ± 3
	J9	1400	170 ± 16
Stillfried	S5 top	Hv 25618	24,430 ± 730 uncal.
	S5 bottom	Hv 25619	22,840 ± 870 uncal.
Paudorf[b]	P2-3	1402	187 ± 12
	P2-9	1401	189 ± 16
	P1-2	1404	106 ± 12
	P1-4	1403	159 ± 20
Göttweig[b]	G1-3	1405	> 300
	G1-1	1406	173 ± 40
	n.a.	1407	> 350
	GII-1	1408	34 ± 3
	GII-4	1409	124 ± 25
Langenlois[c]	LB 2/9	LB 2/9	246 ± 29
	LB 2/10	LB 2/10	> 300
	LB 5/3	LB 5/3	35 ± 2
	LB 5/5	LB 5/5	41 ± 4
	LB 5/10	LB 5/10	41 ± 4
	LB 5/15	LB 5/15	53 ± 4

[a] Thiel et al. 2011a
[b] Thiel et al. 2011b
[c] Thiel et al. 2011c

ing between 23,180 ±120 and 41,700 +3,700/-2,500 yrs. BP (Nigst et al. 2008).

The loess/paleosol sequence investigated has a total thickness of about 10 m, with two distinct pedocomplexes (Fig. 2: 2). The basal loess deposit (J9) is covered by an interglacial pedocomplex (J6–J8). A silty yellowish-brown loess rich in secondary carbonates (unit J5) is exposed on the top of horizon J6. An interstadial paleosol (J4) is present on top of this loess, followed by stratified loamy brownish pellet sands ('Bröckelsande', unit J3). J2 corresponds to a zone of Cryic horizons (J2) (IUSS Working Group WRB 2006) and J1 represents the uppermost loess of the studied sequence.

At this site three luminescence samples were taken (Fig. 2; Thiel et al. 2011b). The lowermost loess unit (J9) was sampled 0.7 m below the pedocomplex (J7 and J8), and the post-IR IRSL dating resulted in an age of 170 ± 16 ka (Table 1). For the 'Bröckelsand' (J3; pellet sands) the depositional age was estimated to 47 ± 3 ka. The uppermost sample originates from the loess unit J1 1.3 m below the surface and was dated to 16 ± 2 ka.

2.3 Stillfried

The Stillfried study site is located in a distance of about 40 km north-east the city of Vienna (Fig. 1). The study site comprises two famous loess/paleosol sequences. Both the 'Stillfrieder Komplex' and the profile of 'Stillfried B' are formed during the Last Glacial/Interglacial cycle. The Stillfried exposures were first mentioned by Boehmker (1917). He described the 'Stillfrieder Komplex' including three humic horizons superimposed on a Bt horizon. Furthermore, the key section of 'Stillfried B' is closely connected with the loess studies of the Austrian loess researcher Julius Fink. Repeatedly, he published on the characteristic weak brownish horizon with its significant content of charcoals (Fink 1954, 1956).

The 'Stillfried B' sequence has been dated repeatedly by radiocarbon dating due to the fact that numerous charcoals are included. The results of Fink (1962), Vogel & Zagwijn (1967) and Rögl & Summesberger (1978) are variable and provided partly age inversions. A more recent discussion is published in Fladerer (2001).

The presented sequence (Fig. 2: 6) is located in the western part of the abandoned brickyard of Stillfried at an altitude of 173 m.

On top of loess strata (S6) three weakly developed BC horizons (S5) with an overall thickness of 1.2 m are situated on top of each other (Peticzka et al. 2010). The basal part of the pedocomplex shows marginally more intense pedogenesis as manifested in bioturbation structures. Charcoals occur in particular in the intermediate section of S5 as well as on top of the uppermost BC horizon (S4).

Recent radiocarbon dating results in a depth of 2.3 m (Hv 25618) respectively 2.6 m (Hv 25619), in a slight inversion of the uncalibrated ^{14}C-dating (Table 1). The sample on top of the pedocomplex records an age of 24,430 ± 730 yr (Hv 25618) and the lower sample is with 22,840 ± 870 yr (Hv 25619) at the same age, respectively slightly younger.

2.4 Paudorf

The village of Paudorf is located on the eastern foothills of the Bohemian massif, 7 km south to the city of Krems.

The studied sequences are exposed in a former brickyard and considered as the type locality of the 'Paudorfer Verlehmungszone' *sensu* Götzinger (1936) and Fink (1976), which was correlated with 'Stillfried A'. The outcrop, which is about 9.5 m deep (Fig. 2) has been described by Fink (1976) and Kovanda et al. (1995) and was analyzed with thermoluminescence by Zöller et al. (1994) and Noll et al. (1994). The published ages differ from each other and do not allow a clear interpretation. At least two pedocomplexes are preserved at this site; the uppermost soil complex corresponds to the prominent 'Paudorfer Bodenbildung', and the basal pedocomplex was correlated with the 'Göttweiger Bodenbildung'.

In profile 1 (Fig. 2: 3a) the pedocomplex of the 'Paudorfer Bodenbildung' (P1/3), developed as a reddish-brown, clay-enriched pedocomplex with crotovina, is intercalated by loess sediments (P1/2 and P1/4).

Profile 2 (Fig. 2: 3b) exhibits a loess/paleosol sequence, which is subdivided in numerous layers and soil horizons, which have never been described in detail. According to Peticzka et al. (2009) a differentiation of at least five pedocomplexes and paleosols is possible. In the basal section of the profile, a well developed dark brown pedocomplex representing at least one interglacial period is present (P2/10). It is overlain by yellowish brown carbonate-rich loess (P2/9) and a brownish paleosol horizon (P2/8). This horizon is overlain by the next loess strata (P2/3–7), which includes the horizons P2/4 and P2/6, which correspond to Cryosols (Reductaquic) according to the IUSS Working Group WRB (2006). Unit P2/2 corresponds to the pedocomplex 'Paudorfer Bodenbildung' described in profile Paudorf 1. In this position the soil horizons are situated close to the surface and thus are disturbed by recent bioturbation.

The position of the luminescence samples is specified in Fig. 2. The uppermost sample was taken in the loess unit P1/2 just above the 'Paudorfer Bodenbildung' (unit P1/3). The measurements of the uppermost sample on top of the 'Paudorfer Bodenbildung' resulted in an age of 106 ± 12 ka for unit P1/2 (Thiel et al. 2011b). The loess unit P1/4 below the 'Paudorfer Bodenbildung' was sampled as a block due to induration. The analyses recorded an age of 159 ± 20 ka (Thiel et al. 2011b).

In profile Paudorf 2, an age of 187 ± 12 ka was obtained for unit P2/3 4.2 m below the surface (P2/3), and the second sample, taken in the loess unit P2/9 (7.9 m below top ground surface), displays a rather similar age (189 ± 16 ka) (Thiel et al. 2011b). Both samples clearly indicate deposition during Marine Isotope Stage (MIS) 6. The underlying pedocomplex (P2/10) originally correlated with the 'Göttweiger Verlehmungszone' (Götzinger 1936), thus developed during MIS 7 or an older interglacial.

2.5 Göttweig

The study site is situated 5 km south of the city of Krems and 2 km north to Paudorf (Fig. 1). Two different sections

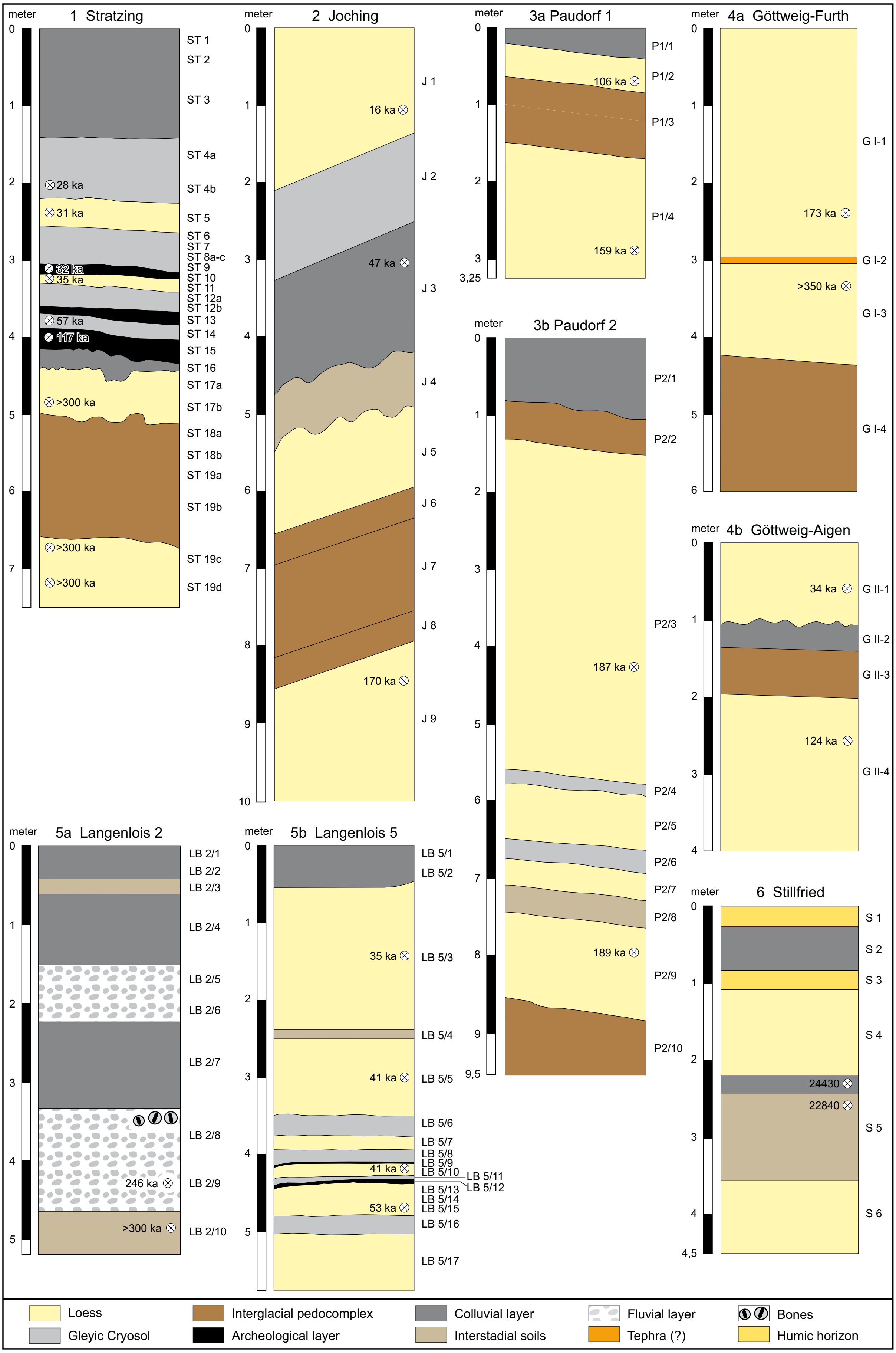

Fig. 2. Overview of the studied sequences on the base of field survey. The sketch provides a generalized and equalized view. The ages are simplified by not showing the errors; they can be depicted from the corresponding section and Table 1.

Abb. 2. Überblick der untersuchten Profile auf der Basis der Geländeaufnahmen. Die Zeichnung gibt eine generalisierte und einander angepasste Sicht. Die Alter sind vereinfacht ohne Fehler dargestellt. Sie können den entsprechenden Unterkapiteln und Tabelle 1 entnommen werden.

were investigated near the monastery of Göttweig, close to the loess sequence in Paudorf (Fig. 2: 4a and b). Section I, Göttweig-Furth (ca. 240 m a.s.l) represents the classical site of the 'Göttweiger Verlehmungszone' *sensu* Bayer (1927) and Götzinger (1936). It is located in a sunken path near the market town of Furth. On the section of Göttweig-Furth, numerous studies have been published reflecting different opinions on the chronology of the pedocomplex 'Göttweiger Verlehmungszone'. For instance, Fink et al. (1976) classified the pedocomplex as Mindel/Riss Interglacial. Kovanda et al. (1995) proposed an older age and allocated it with respect to micromorphological analyses to an interglacial phase inside the Mindel complex. Zöller et al. (1994) allocated the 'Göttweiger Verlehmungszone' as at least antepenultimate interglacial.

With respect to the profile in Göttweig-Aigen, the results of Zöller et al. (1994) indicate that the sequence there belongs to the Last Glacial/Interglacial cycle.

In the section Göttweig-Furth (Fig.2: 4a) the pedocomplex 'Göttweiger Verlehmungszone' (unit GI-4) and the overlying up to 6 m thick sandy-silty yellowish-brown loess is horizontally exposed over several 100 m and situated on top of a Danube terrace of which the chronostratigraphical position is unclear. A continuous thin layer (unit GI-2) can be identified in the loess package; which has the appearance of a tephra. At present, a volcanic component could not be detected by mineralogical analyses.

The luminescence sampling points at Göttweig-Furth are shown in Figure 2 and Table 1. For the loess unit GI-3 (sample 1405) 0.3 m below the tephra band an age of >350 ka was obtained (Thiel et al. 2011b; Table 1). The sample of the loess unit GI-1, 0.6 m above the tephra, was dated to 173 ± 40 ka. About 300 m upslope of this section, a further sample (1407; not shown in Fig. 2) was taken just above the supposed tephra; dating resulted in an age ≥300 ka (Thiel et al. 2011b).

The section Göttweig-Aigen is located in a sunken path near the village of Aigen, where a pedocomplex correlated with the 'Paudorfer Bodenbildung' is exposed (Fink 1976; Fig. 2: 4b). The pedocomplex (unit GII-3) is truncated in its upper parts, as indicated by the lack of an A horizon and a layer of 30 cm thick reworked loess (unit GII-2) covering the soil. Yellowish brown loess (GII-1) is present on top of the redeposited material and below the paleosol (GII-4).

The loess unit GII-1 (Table 1, sample 1408) 0.6 m above the 'Paudorfer Bodenbildung' was dated to 34 ± 3 ka (Thiel et al. 2011b). For the carbonate rich silty loess (unit GII-4), sampled 0.6 m below the 'Paudorfer Bodenbildung' (i.e. 2.45 m below top ground surface), an age of 124 ± 25 ka was obtained.

2.6 Langenlois

The study site is located about 7 km north-east to the city of Krems (Fig. 1) in the area of the Kremser Feld. The loess was deposited in a bay-like depression ('Kremser Bucht'), which was formed tectonically (Wessely 2006). Götzinger (1936) made note of the up to 20 m thick loess sequences at the southern edge of the plateau, whereas Piffl (1955) observed even thicker loess deposition at the easterly slopes of the Kremser Feld. The north-exposed wall of the former brickyard in Langenlois was briefly described by Piffl (1976). In the former brickyard of Langenlois (Fig. 1), fluvial and aeolian deposits are present (Piffl 1976). Until now, for the loess exposures around the market town of Langenlois only few data exist (Smolíková 2003; Fladerer et al. 2005).

Profile LB2: the fluvial sequence

The sediment succession at the east exposed wall of the former brickyard in Langenlois clearly shows a transition from fluvial to eolian deposition (Fig. 2: 5a). The loamy deposits of LB 2/10 display a paleo-surface on which fluvial gravels and sands (LB 2/9 and LB 2/8) were deposited. The fluvial deposits of LB 2/8 include mammal bones, which are mostly in their original anatomical relationships. From a taphonomical point of view it is evident that sedimentation and deposition of carcasses of dead animals or their parts have taken place synchronously during very rapid channel sedimentation without significant relocation (Thiel et al. 2011c). The assemblage speaks in favour of interglacial conditions, but the actual status of taxonomic research does not allow a closer attribution than Middle Pleistocene.

The soil sediment LB 2/7 is superimposed on the fluvial deposits of LB 2/8. It is covered by gravels and sands LB 2/5–6, which reveal another fluvial deposit in the study area.

On top of LB 2/5 a redeposited loam is present (BL 2/4) overlain by a weak paleosol horizon (LB 2/3), which corresponds to an interstadial soil. The uppermost horizons are disturbed by intense land use.

Horizon LB 2/10 was dated to >300 ka (Thiel et al. 2011c; Table 1). The authors emphazised that the derived luminescence age is close to or even beyond the dating limit despite great improvements in latest dating techniques. Thus, a more accurate age cannot be presented. For the fluvial deposits (LB 2/9) luminescence dating resulted in an age of 246 ± 29 ka (Thiel et al. 2011c).

Profile LB5: the eolian sequence

The loess sequence is subdivided by three Cryosols (Reductaquic) (LB 5/6, LB 5/8, LB 5/16) indicating permafrost and associated retention of water (Fig.2: 5b). An initial soil horizon with a weak brownish color is present in the upper part of the sequence (LB 5/4).

A cultural layer containing charcoal fragments can be seen in the lower parts of the profile (LB 5/12).

The record ends with a thick loess strata situated below modern soil sediments.

The dating results indicate that the eolian sequence formed from ~55 ka until ~35 ka (Thiel et al. 2011c; Table 1). The loess unit LB 5/15 was dated to 53 ± 4 ka and for unit LB 5/10 an age of 41 ± 4 ka was obtained. The dating of the approximately 1 m thick homogenous loess of unit LB 5/5 resulted in the same age. The uppermost loess unit (LB 5/3) was dated to 35 ± 2 ka.

3 Discussion

Upper to Middle Last Glacial ages have been obtained in the profiles of Joching, Stratzing and Stillfried. The youngest loess (16 ± 2 ka; Table 1) was found in the upper parts of the sequence in Joching (Fig. 2). Such young loess is exceptional when compared with other loess/paleosol sequences in this area; the dating results indicate intense loess deposition between ~28 ka and ~35 ka. Somewhat younger are the upper profile sections of Stillfried, which were dated by ^{14}C method. In Stillfried ages of 24,430 ± 730 yr BP and 22,840 ± 870 yr BP were obtained. Earlier TL-studies of Zöller et al. (1994) proved younger ages in the upper parts of the Stillfried B sequence.

Alltogether, the sequence in Joching clearly shows that there was loess deposition during the Upper Würmian Pleniglacial. Considering the somewhat older ages in other studied profiles, it can be assumed that erosional processes led to the removal of younger deposits.

Soil formation between ~28 ka and ~35 ka resulted in Cryosols, respectively. Hence, in the studied profiles, there is no evidence for more intense, interstadial pedogenesis in this time span. In the sequence of Willendorf, thin humic horizons are designated to interstadial periods (Haesaerts et al. 1996; Nigst et al. 2008). However, there was proof of only one humic horizon in the sequence of Stratzing (Thiel et al. 2011a), which is not allocated to an interstadial period.

Related to the presented ^{14}C-datings, the age of the paleosol complex in the key section of Stillfried B remains still unclear. It has to be discussed, that published datings are different from each other, measured with variable methods, and uncertainities in the position of samples and sample preparation have to be considered as well. In general ^{14}C-datings are not calibrated in the literature and thus hardly comparable to luminescence results.

However, in Upper Austrian loess profiles there is evidence of intens interstadial pedogenesis at about 29 ka (Terhorst et al. 2002).

The following age cluster lies in the Middle Pleniglacial between ~35 ka and ~57 ka and in that case, one can find primarily loess sediments. Weak and thin Cryic horizons and the loess layers provide evidences for a cold glacial climate.

Furthermore, a prominent colluvial layer in form of pellet sands is present in Joching (47 ± 3 ka). It is underlain by an interstadial brown paleosol of unknown age.

At the sequence in Stratzing differences between former radiocarbon datings and latest luminescence ages are observed. The discrepancy for the central part of the profile (ST 14 and ST 15) is due to redeposition processes and incorporation of older soil material in the slope position. In this context, it has to be highlighted that luminescence dating techniques constrain the time of deposition of sediment, whereas radiocarbon ages refer to the death of an organism. The sediment can therefore be older than incorporated, anthropogenic buried charcoal, wood or artifacts. Controversy may also have arisen because neighboring outcrops were dated, and thus a correlation of individual horizons is hampered.

For the investigations the absence of ages between ~55 ka and ~106 ka it is indicative and might record long lasting and intensive erosion processes in the loess landscape. An age of 106 +/- 12 ka was obtained from the loess on top of the 'Paudorfer Bodenbildung' (Thiel et al., 2011b), which is equivalent to the Stilllfried A complex. Immediately below this pedocomplex ages of 124 ± 25 ka (Göttweig-Aigen), 159 ± 20 ka (Paudorf 1), and 170 ± 16 ka (Joching) were obtained for the loess.

Other sediments older than MIS 5 but younger than MIS 7 were detected in Göttweig-Furth and Paudorf 2.

Concerning the older sediments there are discontinuities, which might be due to the low sampling resolution. However, it is also evident that Lower Austrian loess sequences exhibit great hiatus as shown in Stratzing and Göttweig-Aigen (see Havlíček et al. 1998).

The sequence Langenlois 2 shows an age of 246 ± 50 ka in its basal fluvial deposits. This age is close to the beginning of MIS 7 (Lisiecki & Raymo 2005) and gives an approximation for the faunal remains at this site, which stand for forest to park-like paleoenvironmental conditions and might reflect the beginning of an interglacial (Thiel et al. 2011c).

The next older dating results stand for minimum ages in the range of the given constraints of the dating method. Stratzing and Langenlois record ages of >300 ka for the basal parts, and Göttweig is with an result of ≥350 ka in consistence with older age estimates of Kovanda et al. (1994).

All gathered information in the study sites give evidence of numerous and intensive land forming processes in form of erosion and redeposition.

References

Antl-Weiser, W., Fladerer, F.A., Peticzka, R., Stadler, F.C. & Verginis, S. (1997): Ein Lagerplatz eiszeitlicher Jäger in Grub bei Stillfried. – Archäologie Österreichs, 8/1: 4–20.

Bayer, J. (1927): Der Mensch im Eiszeitalter, I. und II. Teil. – Wien (Deutike).

Boehmker, R. (1917): Exkursionsführer für Stillfried an der March. – p. 13–59, Braunmüller, Wien.

Döppes, D. & Rabeder, G. (1997): Pliozäne und pleistozäne Faunen Österreichs. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 1–411.

Einwögerer, T., Friesinger, H., Händel, M., Neugebauer-Maresch, C., Simon, U. & Teschler-Nicola, M. (2006): Upper Paleolithic infant burials. – Nature, 444: 285.

Fink, J. (1954): Die fossilen Böden im österreichischen Löss. – Quartär, 6: 85–108.

Fink, J. (1956): Zur Korrelation der Terrassen und Lösse in Österreich. – Eiszeitalter und Gegenwart, 7: 49–77.

Fink, J. (1962): Studien zur absoluten und relativen Chronologie der fossilen Böden in Österreich. II; Weitzelsdorf und Stillfried. – Archaeologia Austriaca, 31: 1–18.

Fink, J. (1976): Exkursion durch den österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. Erweiterter Führer zur Exkursion aus Anlass der 2. Tagung der IGCP-Projektgruppe „Quaternary Glaciations in the Northern Hemisphere". – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1: 1–113.

Fink, J. (1978): Exkursion durch den österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. Ergänzungen zu Band 1. – Mitteilungen der Kommission für Quartärforschung der Österreicher Akademie der Wissenschaften, Wien.

Fladerer, F. A. (2001): Die Faunareste von Krems-Wachtberg, Ausgrabung 1930. Jagdwild und Tierkörpernutzung an der Donau vor 27.000 Jahren. – Mitteilungen der Prähistorischen Kommission der Österreichische Akademie der Wissenschaften, Phil.-hist. Kl., 39: 1–97.

Fladerer, F.A., Havlíček, P., Roetzel, R., Salcher, T., Smolíková, L. & Tuzar, J. (2005): Der Steppenwisentfund *(Bison priscus)* von Langenlois-Buriweg, Niederösterreich – Paläontologische und pleistozänstratigrafische Untersuchungen. – Mitteilungen der Kommission für Quartärforschung der Österreichische Akademie der Wissenschaften, 14: 29–40.

Frank, C. (1997): Stillfried-Typusprofile. In: Döppes, D. & Rabeder, G. (Eds.): Pliozäne und pleistozäne Faunen Österreichs. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 123–130, Verlag der Österreichischen Akademie der Wissenschaften, Wien.

Frank, C. & Rabeder, G. (1997): Klimageschichte des österreichischen Plio-Pleistozäns. In: Döppes, D. & Rabeder, G. (Hrsg.): Pliozäne und pleistozäne Faunen Österreichs. – Mitteilungen der Kommission für

Quartärforschung der österreichischen Akademie der Wissenschaften, 10: 375–380.

Götzinger, G. (1936): Das Lößgebiet um Göttweig und Krems an der Donau. – Führer für die Quartär-Exkursionen in Österreich, 1: 1–11.

Haesaerts, P., Damblon, F., Bachner, M. & Trnka, G. (1996): Revised stratigraphy and chronology of the Willendorf II sequence, Lower Austria. – Archaeologia Austriaca, 80: 25–42.

Händel, M., Simon, U., Einwögerer, T. & Neugebauer-Maresch, C. (2008): Loess deposits and the conservation of the archaeological record. The Krems-Wachtberg example. – Quaternary International, 198: 46–50.

Haslinger, E. & Heinrich, M. (2008): Der „Rote Aufschluss" von Langenlois. Pedogenese und Mineralogie von Paläoboden-Sequenzen über Amphibolit. – Abhandlungen der Geologischen Bundesanstalt Wien, 62: 71–79.

Haslinger, E., Smoliková, L., Havliček, P., Roetzel, R., Heinrich, M., Holásek, O., Vachek, M. & Ottner, F. (2009): Pedological and geochemical investigations at the "Red Outcrop" of Langenlois (Lower Austria). – E&G Quaternary Science Journal, 58(2): 135–147.

Havliček, P., Holásek, O., Smolíková, L., Roetzel, R. (1998): Zur Entwicklung der Quartärsedimetne am Südostrand der Böhmischen Masse in Niederösterreich. – Jahrbuch der Geologischen Bundesanstalt, 141: 51–72.

IUSS Working Group WRB (2006): World Reference Base for Soil Resources. – World Soil Resources Reports, 103p. FAO, Rome

Kovanda, J., Smolíková, L. & Horáček, I. (1995): New data on four classic loess sequences in Lower Austria. – Antropozoikum, 22: 63–85.

Lisiecki, L. E. & Raymo, M. E. (2005): A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. – Paleoceanography, 20: 1–17.

Niederhuber, M. (1997): Stratzing/Krems-Rehberg. – In: Döppes, D. & Rabeder, G.: Pliozäne und pleistozäne Faunen Österreichs. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 56–61.

Neugebauer-Maresch, C. (1993): Zur altsteinzeitlichen Besiedlungsgeschichte des Galgenberges von Stratzing/Krems-Rehberg. – Archäologie Österreichs, 4: 10–19.

Neugebauer-Maresch, C. (ed.) (2008): Krems-Hundssteig – Mammutjägerlager der Eiszeit. Ein Nutzungsareal paläolithischer Jäger- und Sammler(-innen) vor 41.000–27.000 Jahren. – Mitteilungen der Prähistorischen Kommission der Österreichischen Akademie der Wissenschaften, 67: 348 pp.

Nigst, P. R., Viola, T.B., Haesaerts, P. & Trnka, G. (2008): Willendorf II. – In: Venus08 - Art and Lifestyle, Symposium Vienna 10.–14. November 2008. – Wissenschaftliche Mitteilungen aus dem Niederösterreichischen Landesmuseum, 19: 31–58.

Noll, M., Leitner-Wild, E. & Hille, P. (1994): Thermoluminescence dating of loess deposits at Paudorf, Austria. – Quaternary Geochronology (Quaternary Science Reviews), 13: 473–476.

Peticzka, R., Riegler, D. & Holawe, F. (2009): Exkursionsführer der 28. Jahrestagung des Arbeitskreises Paläopedologie der Deutschen Bodenkundlichen Gesellschaft. Universität Wien (unpublished; http://www.dbges.de/wb/pages/arbeitsgruppen/palaeopedologie/aktivitaeten.php).

Peticzka, R., Holawe, F., Riegler, D. (2010): Structural analyses on the modified paleosol-sequence of "Stillfried B" with high resolution measurements of selected laboratory parameters. – Quaternary International, 222: 168–177.

Piffl, L. (1955): Exkursion von Krems bis Absberg. – Verhandlungen der Geologischen Bundesanstalt, Sonderheft: 70–78.

Piffl, L. (1976): Stop 3/4: Ziegelwerk W Langenlois (Hammerer). – In: Fink, J. (ed.): Exkursion durch den österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. Erweiterter Führer zur Exkursion aus Anlass der 2. Tagung der IGCP-Projektgruppe „Quaternary Glaciations in the Northern Hemisphere". – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1: 113 pp.

Rögl, F. & Summesberger, H., (1978): Die geologische Lage von Stillfried. – Forschungen in Stillfried, 3: 75–86.

Smolíková, L. (2003): Bericht 2002 über Mikromorphologie, Typologie und Stratigraphie quartärer Böden vom Buriweg in Langenlois auf Blatt 38 Krems. – Jahrbuch der Geologischen Bundesanstalt, 143/3: 506–507.

Smolíková, L. & Havlíček, P. (2007): Bericht 2005 und 2006 über mikromorphologische Untersuchungen von quartären Böden im Gebiet des unteren Kamptales auf den Blättern 21 Horn und 38 Krems. – Jahrbuch der Geologischen Bundesanstalt, 147/3–4: 682–683.

Terhorst, B., Frechen, M. & Reitner, J. (2002): Chronostratigraphische Ergebnisse aus Lößprofilen der Inn- und Traun-Hochterrassen in Oberösterreich. – Zeitschrift für Geomorphologie N.F., 127: 213–232.

Thiel, C., Buylaert, J.-P., Murray, A. S., Terhorst, B., Hofer, I., Tsukamoto, S. & Frechen, M. (2011a): Luminescence dating of the Stratzing loess profile (Austria) – Testing the potential of an elevated temperature post-IR IRSL protocol. – Quaternary International, 234: 23–31.

Thiel, C., Buylaert, J.-P., Murray, A. S., Terhorst, B., Tsukamoto, S. & Frechen, M. (2011b): Investigating the chronostratigraphy of prominent palaeosols in Lower Austria using post-IR IRSL dating. – E&G Quaternary Science Journal, accepted.

Thiel, C., Terhorst, B., Jaburová, I., Buylaert, J.-P., Murray, A. S., Fladerer, F. A., Damm, B., Frechen, M. & Ottner, F. (2011c): Sedimentation and erosion processes in Middle to Late Pleistocene sequences exposed in the brickyard of Langenlois/Lower Austria. Geomorphology. DOI 10.1016/j.geomorph.2011.02.011.

Vogel, J. C. & Zagwijn, W. H. (1967): Groningen radiocarbon dates VI. - Radiocarbon, 9: 63–106.

Wessely, G. (2006): Geologie der österreichischen Bundesländer, Niederösterreich. – 416 S., Wien (Geologische Bundesanstalt).

Zöller, L., Oches, E.A., McCoy, W.D. (1994): Towards a revised chronostratigraphy of loess in Austria with respect to key sections in the Czech Republic and in Hungary. – Quaternary Geochronology (Quaternary Science Reviews), 13: 465–472.

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Editoral

This section of the special volume of E&G Quaternary Science Journal published for the XVIII INQUA congress in Bern 2011 includes four articles dealing with the Quaternary stratigraphy of the Northern Alpine Foreland.

It has to be remembered that the Northern Alpine Foreland played an important role in scientific history of Quaternary research. It was in Switzerland where the theory of Quaternary glaciations was originally developed in the early 19th century by Ignatz Venetz and others, before it got later globally promoted by Louis Agassiz. In Southern Germany, Albrecht Penck and Eduard Brückner set a landmark at the dawn of the 20th century by introducing the first complex stratigraphy of Quaternary glaciations, with the famous subdivision into four glaciations named Günz, Mindel, Riss and Würm, separated by interglacials.

In 1990, the working group on Quaternary Stratigraphy of the Alpine Foreland (AGAQ) was established under the lead of Karl-Albert Habbe (1928–2003). The aim of this group is to improve correlations of stratigraphic schemes in different regions of the Northern Alpine Foreland.

After 20 years of work, the XVIII INQUA congress 2011 in Bern is considered as the most appropriate occasion to present the work of AGAQ to an international audience. The four contributions from Switzerland, Southern Germany (Baden-Württemberg, Bavaria) and Austria review and discuss regional stratigraphic schemes in detail. It has been the aim to present particular field evidences forming the basis of the subdivision of the Quaternary. Authors were given the possibility to present their arguments in detail and argue towards relevant specialities of local Quaternary stratigraphic schemes. It is important to note that all the stratigraphic schemes presented are actually used in the maps of the different Geological Surveys. We thank the referees for the sometimes difficult task of reviewing papers that are beyond the norm usually found in scientific journal, for example with regard to length.

It is a difficult task to decipher the problems of different approaches, assumptions and natural environments in the papers. May the following figures and tables offer some preliminary ideas: Fig. 1 gives an overview of the investigated areas. Fig. 2 displays a section through the investigated areas. Tab. 1 opposes the titles of the presented papers, main targets of the authors and main stratigraphic approaches. Tab. 2 gives information about important investigated subjects and Tab. 3 summarizes the relation to the scientific work of Albrecht Penck.

We can assume

- that it is a strange idea to divide and investigate the Alpine ice cap along country's frontiers (Fig. 1).
- that during the last glacier maximum the Alpine ice was not equally shared in the Alpine Forelands of Switzerland, Baden-Württemberg, Bavaria and Austria (Fig. 2).
- that details of stratigraphical approaches differ (Tab. 1)
- that glacial, proglacial and periglacial environments are not equally assessed (Tab. 2)
- that axioms are the base of our research (Tab. 3)
- that before the correlation of different stratigraphical results the basic axioms, points of view and the investigated subjects have to be examined.

One of our numerous questions about correlation concerns the outline of the formerly glaciated areas: it is well accepted that major glaciers react more slowly to climate change than small glaciers. Is it meaningful to compare our observations of terminal moraines from the giant foreland glaciers in the west to the small valley glaciers in the east?

Definitely we have to go on with our (working group) discussions…! And the four presented papers offer exiting details about local scientific approaches, scope, chronology, stratigraphy and landscape developments…!

Thank you very much all the colleagues, who supported this volume: Frank Preusser for networking and special advice! Reviewers for many valuable comments! Geozon handled the manuscripts professionally! Helene Pfalz-Schwingenschlögl (Universtät für Bodenkultur Wien) designed several drawings! DEUQUA president Margot Böse and the DEUQUA steering committee offered generously to publish in E&G! Members of AGAQ (www.baunat.ac.at) discussed stratigraphy during 20 years.

Last but not least INQUA congress president Christian Schlüchter helped, encouraged and provided (together with his team) the fantastic international audience during INQUA congress 2011 in Berne (Switzerland)! Thank's a lot!

Markus Fiebig
Chair of the AGAQ community

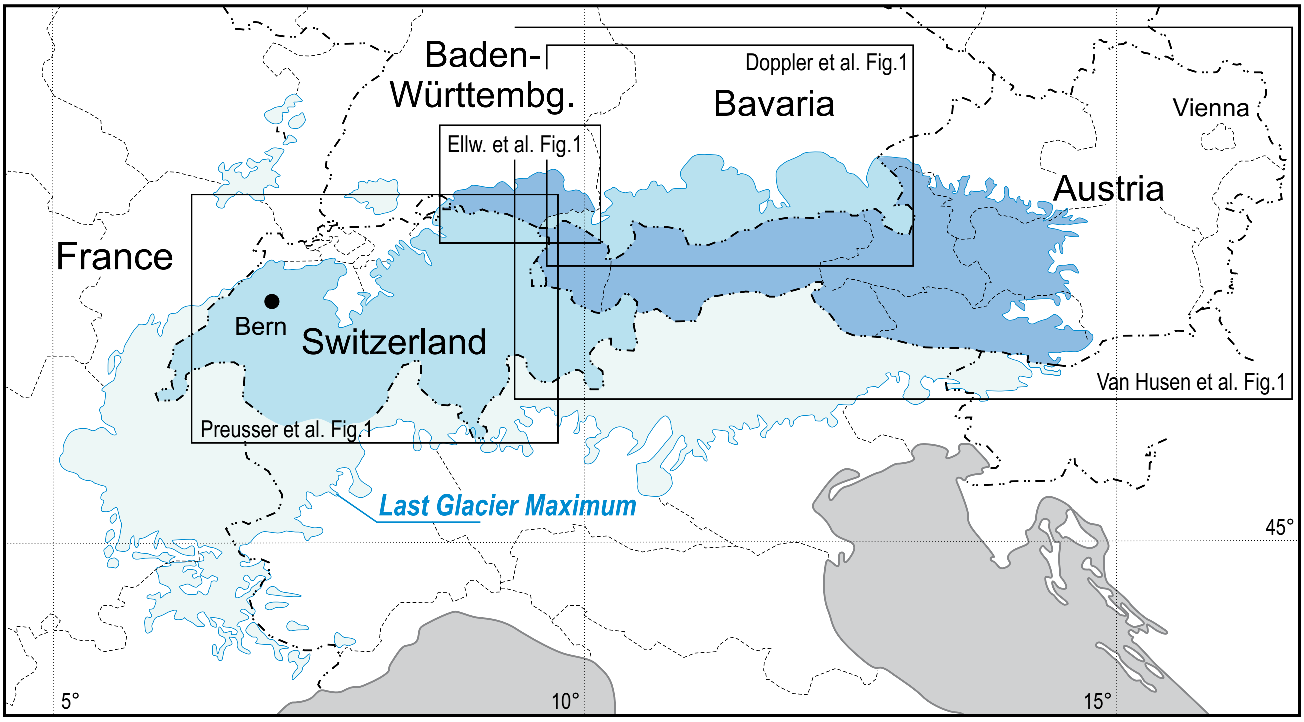

Fig. 1: Contemplating the Alpine ice cap, we notice that Switzerland was almost entirely covered by ice during the last glacier maximum (in light blue). PREUSSER *et al. focused on the northern part of Switzerland in their contribution. In Austria the last glacier maximum covered only the western, inner alpine part of the country (dark blue). Baden-Württemberg and Bavaria were covered by ice only in their southern most parts. The investigated Rhine glacier area (Fig. 1 of* ELLWANGER *et al.) is in comparison to the other formerly four glaciated and investigated areas smaller. However, all countries intersect in the Rhine glacier area. It is the transition zone between Rhenish drainage to the west (and north) and Danubian drainage to the east.*

Abb. 1: Beim Betrachten der alpine Eiskappe (während der letzten Eiszeit) fällt zunächst auf, dass die Schweiz annähernd komplett vergletschert war (in hellblau dargestellt). Der Artikel von PREUSSER *et al. beschäftigt sich hauptsächlich mit dem ehemaligen Nordrand dieser Vergletscherung. In Österreich bedeckten die Gletscher während des letzten Maximalstands vor allem westliche und inneralpine Landesteile (in dunkelblau dargestellt). Baden-Württemberg und Bayern waren nur in den südlichsten Anteilen eisbedeckt. Das Rheingletschergebiet (vgl. Abb. 1,* ELLWANGER *et al.) ist deutlich kleiner als die anderen untersuchten Gebiete. Aber gerade in diesem kleineren Untersuchungsgebiet treffen die vier untersuchten Länder zusammen. Dieses Gebiet ist gleichzeitig auch der Übergangsbereich zwischen der Rheinischen Entwässerung nach Westen (und Norden) und der Danubischen Entwässerung nach Osten.*

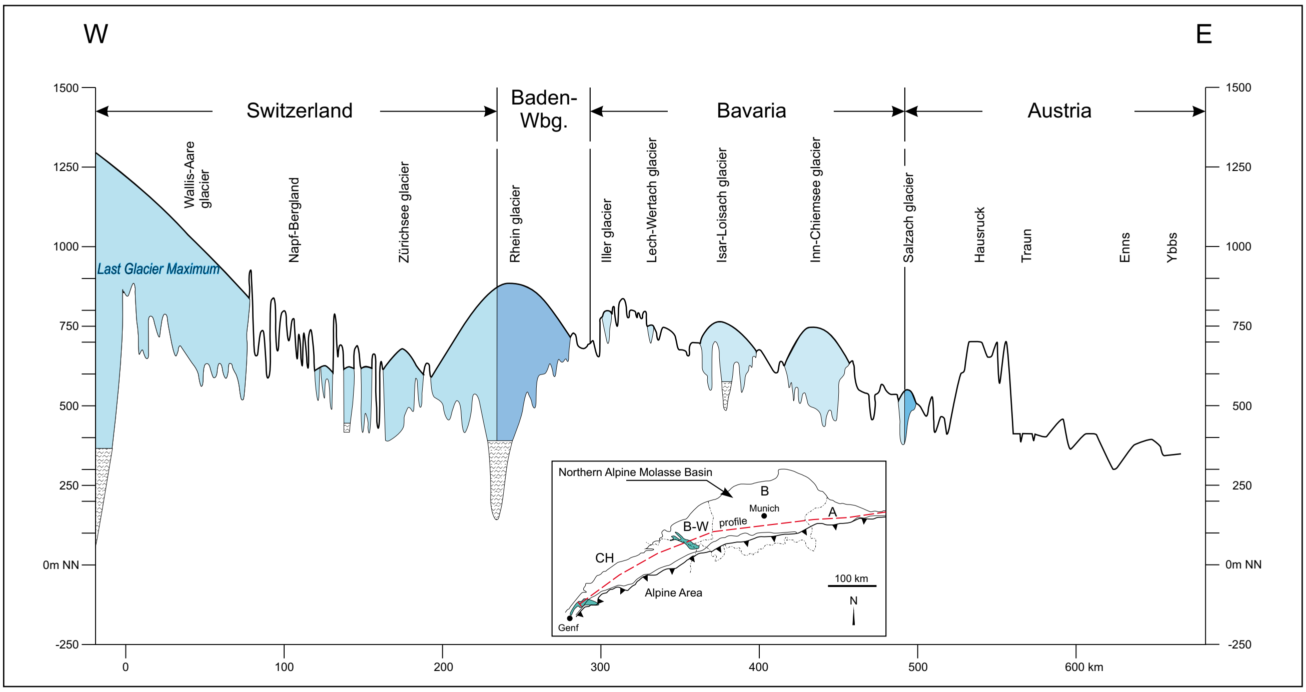

Fig. 2: A section through the Alpine Foreland in front of the tectonic Alpine border during the last glacier maximum. The section displays the thick ice cover in the western Rhenish part. The foreland ice thins out to the east. This difference of ice extent seems to be controlled by Alpine topography and precipitation and it is an open question if stratigraphic correlations between the eastern and western Alpine Foreland are straightforward.

Abb. 2: Ein Schnitt durch das Alpenvorland vor der Front der tektonischen Alpenstirn während des letzten Gletschermaximalstands. Der Schnitt zeigt die mächtige Eisbedeckung im westlichen rheinisch entwässernden Teil. Nach Osten dünnt das Vorlandeis aus. Dieser Unterschied in der Eisbedeckung dürfte durch die alpine Gebirgstopographie und die Niederschlagsverteilung ausgelöst worden sein und wirft die Frage auf, ob einfache Korrelationen zwischen dem westlichen und dem östlichen Teil möglich sind.

*Tab. 1: A comparison of title, main target and main stratigraphic systems **based on the authors own assessment in the abstracts**. To study abstracts and titles is naturally a first approach to understand main thoughts and concerns of the authors. For example, the titles indicate that* Preusser *et al. and* Ellwanger *et al. focus more on local earth history while* Doppler *et al. and* van Husen & Reitner *present their nomenclature and system. To correlate stratigraphic results is not simple and needs careful examination of the authors point of view and of the investigated subjects.*

*Tab. 1: Ein Vergleich der Titel, der angepeilten Inhalte und der hauptsächlichen stratigraphischen Gliederungsansätze **basierend auf dem Textkondensat der Autoren in Form ihrer jeweiligen Text-Zusammenfassungen**. Den Titel und den Abstrakt einer Publikation als erstes zu lesen ist natürlich der normale Zugang zu Publikationen. Genaueres Studium dieser Zusammenfassungen kann vor allem beim Vergleichen ähnlicher Artikel zu besonders betonten Aspekten führen. Ein einfaches Beispiel: schon vom Titel her scheinen* Preusser *et al. und* Ellwanger *et al. vor allem die Landschafts- und Erdgeschichte mit ihren Artikeln vermitteln zu wollen.* Doppler *et al. und* van Husen & Reitner *dürften dagegen ihre stratigraphischen Begrifflichkeiten und das dazugehörige System (der Geologischen Karten) hauptsächlich im Sinn gehabt haben. Solche unterschiedlichen (Text-)Ansätze zu korrelieren ist weder simpel, noch kann dabei auf ein genaues Studium der subjektiven Ausgangspunkte der Bearbeiter und der objektiven Unterschiede der untersuchten Objekte verzichtet werden.*

Papers (this volume) *Status 30.04.11*	**Preusser et al.**	**Ellwanger et al.**	**Doppler et al.**	**van Husen & Reitner**
Title of the paper	"Quaternary glaciation history of northern Switzerland"	"The Quaternary of the southwest German Alpine Foreland (Bodensee-Oberschwaben…)"	"Quaternary stratigraphy of southern Bavaria"	"An outline of the Quaternary stratigraphy of Austria"
Main target of the paper mentioned in the abstract	To present "a revised glaciation history of northern …" Switzerland	"The glacial sediments and landforms are described by units…" in Baden-Württemberg	"A review of current stratigraphical systems … of Southern Bavaria …"	"An overview of the Quaternary stratigraphy in Austria is given"
Main stratigraphical systems mentioned in the abstract	"MN 17", "…glacial cycle… comprises.. independent glacial advances", "radiocarbon chronology"	"chronostratigraphical system", "lithostratigraphic system", "…a system of unconformity bounded sedimentary units…", "terrace stratigraphy"	"Climate and Terrace stratigraphy", "…traditional classification after Penck & Brückner (1901–1909) and its enhancements …" , "so-called morphostratigraphy",	"Mappable depositional units", "lithostratigraphy (lithic properties)", "allostratigraphy (e.g. unconformities)", "Paleomagnetically correlated…" Marine Isotope Stages (MIS)

*Tab. 2: Main investigated sedimentary units, landscape elements and landscape developments (**again based on the authors own assessment in the abstracts**). As the investigated landscapes are different the authors observe and value different subjects. For example "Deckenschotter" seems to be a very important key word in the west (*Preusser *et al.,* Ellwanger *et al.). Loess and loess-paleosol-sequences seem to be crucial for the stratigraphy of Austria. The investigated landscape has an impact on researchers approach to stratigraphy.*

*Tab. 2: Hauptsächlich untersuchte Sedimente, Landschaftselemente und Landschaftsentwicklungen (**wiederum auf der Basis der Textkondensate der Autoren in Form ihrer jeweiligen Text-Zusammenfassungen**). Da die untersuchten Landoberflächen unterschiedlich sind, haben die Autoren unterschiedliche Beobachtungen gesammelt und bewerten diese Objekte unterschiedlich. Zum Beispiel „Deckenschotter" scheinen ein ganz wichtiges Stichwort für die Stratigraphie im Westen zu sein (*Preusser *et al.,* Ellwanger *et al.). Löss und Löss-Paläoboden-Sequenzen sind offenbar sehr wichtige und tragende Elemente der Stratigraphie in Österreich. Solche unterschiedlichen Landschaften dürften einen Einfluss auf den Zugang der WissenschaftlerInnen zur Stratigraphie haben.*

Authors Papers (this volume) *Status 30.04.11*	**Preusser et al.**	**Ellwanger et al.**	**Doppler et al.**	**van Husen & Reitner**
Important sedimentary units mentioned in the abstract	"multiphase gravels intercalated by till and overbank deposits ("Deckenschotter")…", "two complex units (Höhere… Tiefere Deckenschotter).."	"… fluvial gravels… (Deckenschotter)…", "glacial and meltwater deposits", "glacial till"	"continental deposits"	"…fluvial accumulation and loess deposition..", "…loess-paleosol-sequences..", "..proglacial sediments topped by basal till…"
Main landscape elements mentioned in the abstract	"Alpine Rhine", "… differences in the base level.., "…most extensive glaciation…"	"Bodensee amphitheatre", "Rhineglacier", "alpine Rhine valley", "terrace levels"	"Terrace sequences were crucial…", "terminal moraines constitute Glaziale Serien with associated terraces…"	"…terminal moraines linked with terrace bodies…", "major glaciations"
Main (local) landscape development mentioned in the abstract	"…Deckenschotter are separated from Middle Pleistocene by a period of important erosion… re-direction of the Alpine Rhine…(Middle Pleistocene Reorganisation…", "… Middle-late Pleistocene comprises 4 or 5 glaciations…"	"Transformation of alpine margin from a ramp of foothills to …overdeepened amphitheatre…", "…evolving alpine source…", "foothill landscape towards present topography.."	No explicit landscape development in the focus of the abstract	No explicit landscape development mentioned, "…climate deteriorations and consequently glaciations…"

Tab.3: Albrecht Penck (1858–1945) provided in his publications axioms for Quaternary research like the base level concept. In the Bavarian Alpine foreland he derived his model of four glaciations. In the text body by Doppler et al. addicted about 13 % of all their mentioned citations to Penck. In the other papers between 5.6 and 7.8 % of citations are dedicated to Penck. Use of Pencks paradigm is still a very important factor. His scientific legacy includes famous local studies and general orientations for several generations of researchers.

Tab. 3: Albrecht Penck (1858–1945) lieferte in seinen Publikationen grundlegende Annahmen (Axiome) für die nachfolgende Quartärforschung wie zum Beispiel das so genannte Leitfossil der Penck'schen Quartärstratigraphie: die Schotterunterkante. Im Bayerischen Alpenvorland hat er sein Modell der vier Eiszeiten abgeleitet. Doppler et al. haben 13 % ihrer Zitate im Text Penck gewidmet. In den anderen Publikationen weisen zwischen 5,6 und 7,8 % aller Zitate auf Penck hin. Die Penck'schen Grundannahmen (Paradigmen) werden also auch 100 Jahre nach ihrer Publikation als sehr wichtig erachtet. Sein wissenschaftliches Vermächtnis enthält neben generellen Leitlinien für Forschergenerationen auch berühmt gewordene Detailstudien.

Papers (this volume) *Status 30.04.11*	**Preusser et al.**	**Ellwanger et al.**	**Doppler et al.**	**van Husen & Reitner**
Total number of references	70 (100 %)	56 (100 %)	167 (100 %)	125 (100 %)
"Penck" citations in references	1 (1.4 %)	1 (1.8%)	4 (2.4 %)	3 (2.4 %)
Total number of citations in text body (without fig.)	125 (100 %)	115 (100 %)	447 (100 %)	312 (100 %)
"Penck" citations in text	7 (5.6 %)	9 (7.8 %)	58 (13 %)	19 (6 %)

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Quaternary glaciation history of northern Switzerland

Frank Preusser, Hans Rudolf Graf, Oskar Keller, Edgar Krayss, Christian Schlüchter

Abstract: A revised glaciation history of the northern foreland of the Swiss Alps is presented by summarising field evidence and chronological data for different key sites and regions. The oldest Quaternary sediments of Switzerland are multiphase gravels intercalated by till and overbank deposits ('Deckenschotter'). Important differences in the base level within the gravel deposits allows the distinguishing of two complex units ('Höhere Deckenschotter', 'Tiefere Deckenschotter'), separated by a period of substantial incision. Mammal remains place the older unit ('Höhere Deckenschotter') into zone MN 17 (2.6–1.8 Ma). Each of the complexes contains evidence for at least two, but probably up-to four, individual glaciations. In summary, up-to eight Early Pleistocene glaciations of the Swiss alpine foreland are proposed. The Early Pleistocene 'Deckenschotter' are separated from Middle Pleistocene deposition by a time of important erosion, likely related to tectonic movements and/or re-direction of the Alpine Rhine (Middle Pleistocene Reorganisation – MPR). The Middle-Late Pleistocene comprises four or five glaciations, named Möhlin, Habsburg, Hagenholz (uncertain, inadequately documented), Beringen, and Birrfeld after their key regions. The Möhlin Glaciation represents the most extensive glaciation of the Swiss alpine foreland while the Beringen Glaciation had a slightly lesser extent. The last glacial cycle (Birrfeld Glaciation) probably comprises three independent glacial advances dated to ca. 105 ka, 65 ka, and 25 ka. For the last glacial advance, a detailed radiocarbon chronology for ice build-up and meltdown is presented.

[Quartäre Vergletscherungsgeschichte der nördlichen Schweiz]

Kurzfassung: Eine revidierte Vergletscherungsgeschichte des nördlichen Vorlandes der Schweizer Alpen wird vorgestellt, basierend auf Feldbefunden und chronologischen Daten von verschiedenen Schlüssellokalitäten und Regionen. Die ältesten quartären Sedimente der Schweiz sind mehrphasige Kiese, in die Till und Hochflutsedimente eingeschaltet sind ('Deckenschotter'). Bedeutende Unterschiede im Basisniveau der Schotterablagerungen erlauben die Unterscheidung zweier komplex augebauter Einheiten ('Höhere Deckenschotter', 'Tiefere Deckenschotter'), die durch eine Phase bedeutender Einschneidung getrennt sind. Säugetierreste stellen die ältere Einheit ('Höhere Deckenschotter') in die Zone MN 17 (2.6–1.8 Ma). Jeder der Komplexe enthält Belege für zumindest zwei, möglicherweise sogar bis zu vier eigenständige Eiszeiten, woraus sich in Summe bis zu acht frühpleistozäne Vergletscherungen des Schweizer Alpenvorlands ergeben. Die frühpleistozänen Deckenschotter sind von mittelpleistozänen Ablagerungen durch eine Zeit bedeutender Erosion getrennt, die wahrscheinlich durch tektonische Bewegungen und/oder eine Umleitung des Alpenrheins verursacht wurde (Mittelpleistozäne Reorganisation – MPR). Das Mittel-/Spätpleistozän beinhaltet vier oder fünf Eiszeiten, die nach ihren Schlüsselregionen als Möhlin-, Habsburg-, Hagenholz- (unsicher, unzureichend belegt), Beringen- und Birrfeld-Eiszeit benannt sind. Die Möhlin-Eiszeit repräsentiert die grösste Vergletscherung des Schweizer Alpenvorlandes, während die Beringen-Eiszeit von nur wenig geringerer Ausdehnung war. Der letzte Glazialzyklus (Birrfeld-Eiszeit) umfasst wahrscheinlich drei eigenständige Gletschervorstösse, die auf ca. 105 ka, 65 ka und 25 ka datiert wurden. Für den letzten Eisvorstoss wird eine detaillierte Radiokohlenstoffchronologie für den Eisaufbau und das Abschmelzen präsentiert.

Keywords: *Alps, glaciation, stratigraphy, chronology, glacial deposits*

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1 Introduction

The Swiss Alps are the area where the theory of past glaciations of the lowlands was originally developed by Perraudin and published by Venetz (1833). The glaciation theory was later further elaborated and promoted by, for example, Agassiz (1837) and de Charpentier (1841), but it was again Venetz (1861) who brought up the idea that glaciers may have reached the lowlands several times in the past. The tetra-partition of the ice age was later internationally established by Penck & Brückner (1901/09) who observed four different levels of former out-wash plains in the Iller Valley, Bavaria, each of which is expected to represent a discrete glaciation. Proof of the glacial character of the gravel deposits is given by the connection of the younger three units to glacial series, i.e. terminal moraine ridges and glacial basins. The four glaciations deduced from this evidence have been named after small rivers in Bavaria (from old to young: Günz, Mindel, Riss, and Würm), and this stratigraphical scheme has been adopted at least for some time in many parts of the world. It is important to note that the original Penck & Brückner (1901/09) scheme was later modified and extended by three further glacial complexes (Donau: Eberl 1930; Biber: Schaefer 1957; Haslach: Schreiner & Ebel 1981). However, until now these stratigraphical units have not been recognised outside southern Germany.

In Switzerland, the four-fold Penck & Brückner (1901/09) concept was widely accepted for a long time. It has been assumed that the four glaciations found in Bavaria

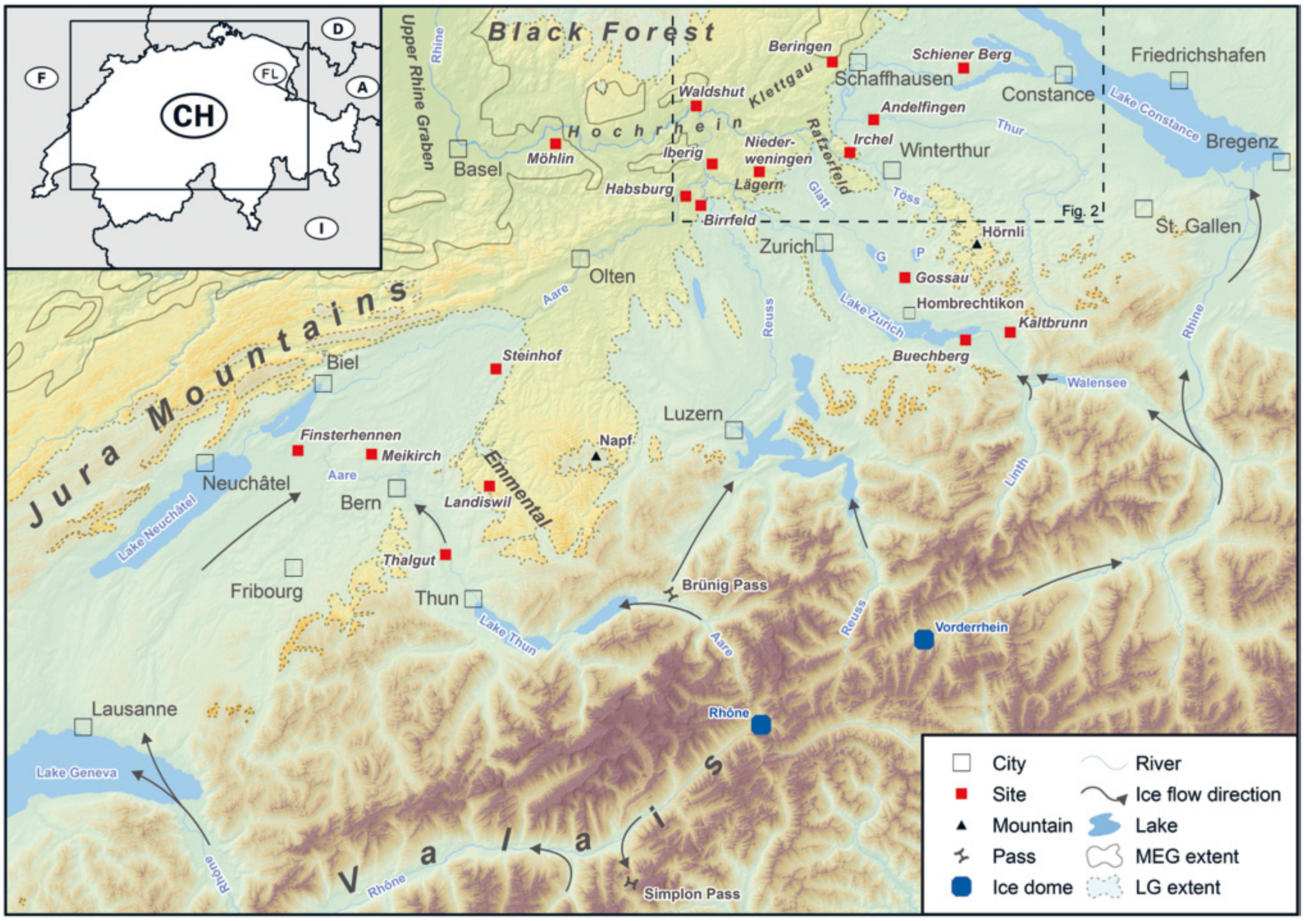

Fig. 1: Overview map of the study in northern Switzerland, with the location of ice domes and ice flow directions (after FLORINETH 1998; FLORINETH & SCHLÜCHTER 1998; KELLY et al. 2004), and the location of key regions and sites mentioned in the text (G = Greifensee; P = Pfäffikersse; LG = Maximum extent of the Last Glaciation; MEG = Extent of the Most Extensive Glaciation).

Abb. 1: Übersichtskarte des Untersuchungsgebietes in der Nordschweiz mit der Lage von Eisdomen und Eisflussrichtungen (nach FLORINETH 1998; FLORINETH & SCHLÜCHTER 1998; KELLY et al. 2004), sowie der Lage von Schlüsselregionen und Örtlichkeiten, die im Text vermerkt sind (G = Greifensee; P = Pfäffikersse; LG = Maximale Ausdehnung der letzten Vergletscherung; MEG = Ausdehnung der Grössten Vergletscherung).

are represented by the morphological features of Low Terrace (Würm), High Terrace (Riss), 'Tiefere Deckenschotter' (Mindel), and 'Höhere Deckenschotter' (Günz). An alternative view of the glaciation history of the Swiss lowlands was introduced by SCHLÜCHTER (1988), who combined geomorphological observations with detailed logging of sections and establishing lithostratigraphical models. According to this scheme, glaciers reached the lowlands of Switzerland at least 15 times during the Quaternary, which is much more often than previously assumed.

This contribution aims at providing a comprehensive overview of the present knowledge of the Quaternary history of the northern foreland of the Swiss Alps, based on evidence for different key areas and sites (locations are given in Fig. 1). The oldest Quaternary deposits are the so-called 'Deckenschotter' of northern Switzerland, which probably comprise the largest part of the Early Pleistocene development. The new terminology introduced by GRAF (2009a) comprises five Middle to Late Pleistocene glaciations (from old to young): Möhlin, Habsburg, Hagenholz, Beringen, and Birrfeld. Evidences for this new stratigraphical scheme will be summarised and are mainly based on previous studies by GRAF (2009a) and KELLER & KRAYSS (2010). As correlations with the stratigraphic scheme of PENCK & BRÜCKNER (1901/09) are not yet reliably established, this article will desist from using nomenclature established for Bavaria. Detailed reviews of the Late Quaternary environmental history of the region and glacial dynamics are not given here, as these have already been provided by PREUSSER (2004) and IVY-OCHS et al. (2008, 2009).

2 Geological, topographic and palaeo-glaciological setting

The area considered here comprises the northern foreland of the Swiss Alps from the eastern edge of Lake Neuchâtel in the west to the western banks of Lake Constance in the east (Fig. 1). The Alps that form the southern border of the study area consist mainly of limestone and other sediments in their outer parts, and a variety of different magmatic and metamorphic rocks in their inner parts. The petrography of pebbles and boulders found in glacial deposits in the foreland has been used to reconstruct past ice flow patterns. To the north, the region of interest is bounded by the chain of the Jura Mountains, with peaks reaching altitudes of up to 1700 m a.s.l. and consisting mainly of limestone. The Jura mountain range has acted as a barrier with a major impact on ice flow in the western part of the region. To the east, the Jura mountain range lowers and Jurassic limestone is finally covered by Molasse sediments. The latter is debris eroded from the emerging Alps during the Tertiary and consists mainly of modestly cemented sandy to silty rocks with some conglomerates. In general, the Molasse area is made up of rolling hills, but in many areas glacial and fluvial erosion have formed pronounced relief and major valley drainage networks. The central part of the study area is made up of the midlands of Emmental and the Napf Mountains, the latter reaching a maximum height of 1408 m a.s.l. This area also acted as a barrier during past glaciations and was, apart from local glaciations in the highest parts of the Napf Mountains, not covered by ice during the Last Glaciation (Schlüchter 1987a; Bini et al. 2009; Fig. 1). Further to the east, the Hörnli Mountains similarly acted as a barrier dividing the Linth-Rhine Glacier and Lake Constance-Rhine Glacier during past glaciations (Keller & Krayss 2005a; Fig. 1).

The entire northern foreland of the Swiss Alps, including the Lake Constance basin, is currently draining through the Hochrhein and the Upper Rhine Graben towards the North Sea (Fig. 1). In contrast, the foreland of the Bavarian and Austrian Alps drains through the River Danube towards the east, into the Black Sea. The reason for the much more pronounced relief in the Swiss Alpine foreland, compared to its continuation in the east, is probably due to the fact that the base level of the drainage is relatively low, with the subsiding Upper Rhine Graben, bounded to the east by the (still up-lifting?) massif of the Black Forest.

Quaternary glaciations of the foreland of the Swiss Alps were characterised by networks of transection glaciers that flow from the accumulation areas in the high mountains following major pre-existing valleys (Fig. 1). Florineth (1998), Florineth & Schlüchter (1998), and Kelly et al. (2004) demonstrated for the Last Glaciation that several centres of ice accumulation existed to the south of the main alpine chain. This implies that moisture was transported from the south rather than the north, as is currently the case, indicating a significantly different atmospheric circulation pattern over central Europe during glacial times compared to the present (Florineth & Schlüchter 2000). For the western part of our study area, the ice dome in the southern Valais was of major importance as it fed glaciers that flowed down-valley to Lake Geneva. There, part of the ice turned NE towards the Aare Valley, whereas the rest continued towards the SW following the Rhône Valley. In most previous studies, this ice mass was referred to as the Rhône Glacier. Kelly et al. (2004), however, have shown that Rhône Glacier *sensu stricto* (i.e. the present glacier located in the uppermost part of Valais) was blocked by ice from the southern Valais and was forced over Simplon Pass towards the south (Fig. 1).

In the area of the city of Bern, a confluence situation of the Valais Glacier and Aare Glacier, the latter originating from the Bernese Oberland, existed during the Last Glaciation and possibly also during older glaciations. Further up-valley, part of Aare Glacier flowed over Brünig Pass to join the Reuss Glacier in Central Switzerland (Fig. 1). To the east, the Linth Glacier and the (western) Walensee branch of the Rhine Glacier joined and continued further to the north. The main (eastern) branch of the Rhine Glacier formed a large piedmont ice lobe at the eastern edge of the study area, covering the area of the present Lake Constance.

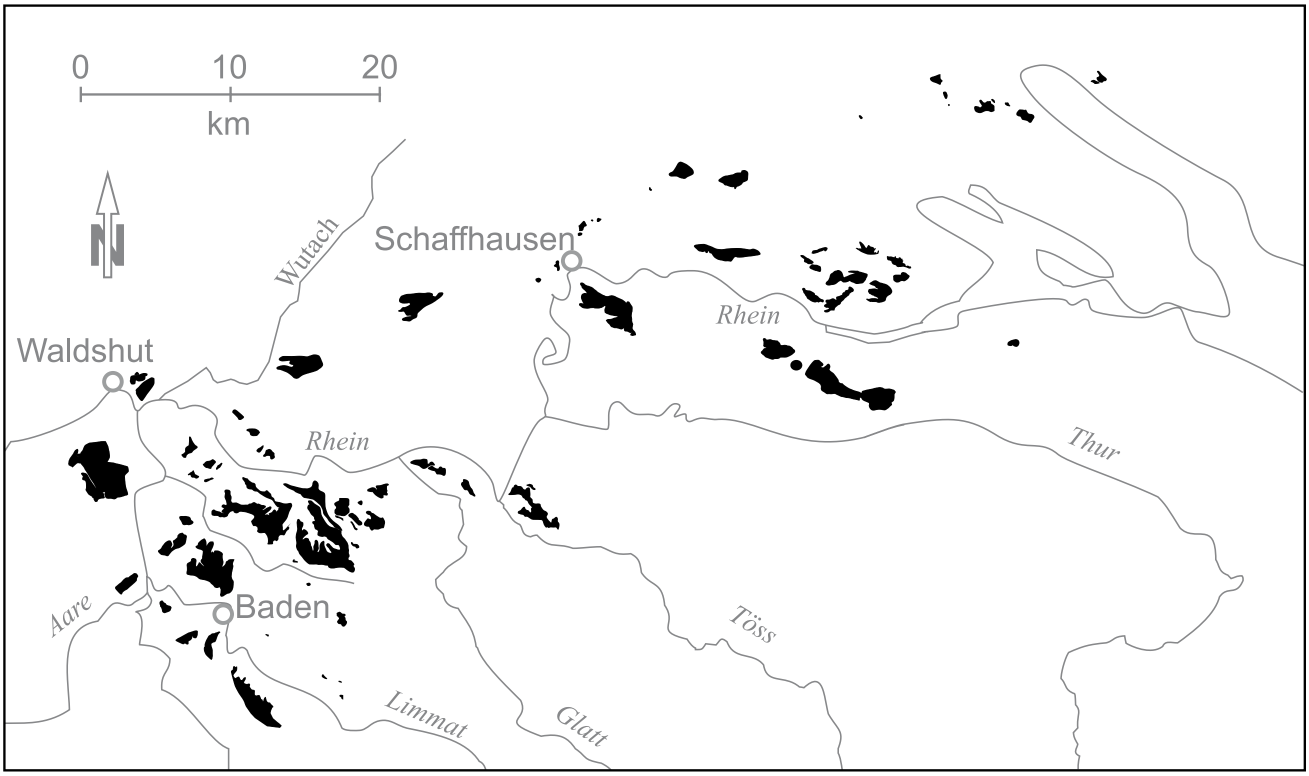

Fig. 2: Distribution of 'Deckenschotter' in northern Switzerland (modified after Graf 1993, 2009b).

Abb. 2: Verteilung der Deckenschotter in der Nordschweiz (modifiziert nach Graf 1993, 2009b).

E&G / Vol. 60 / No. 2–3 / 2011 / 282–305 / DOI 10.3285/eg.60.2-3.06 /

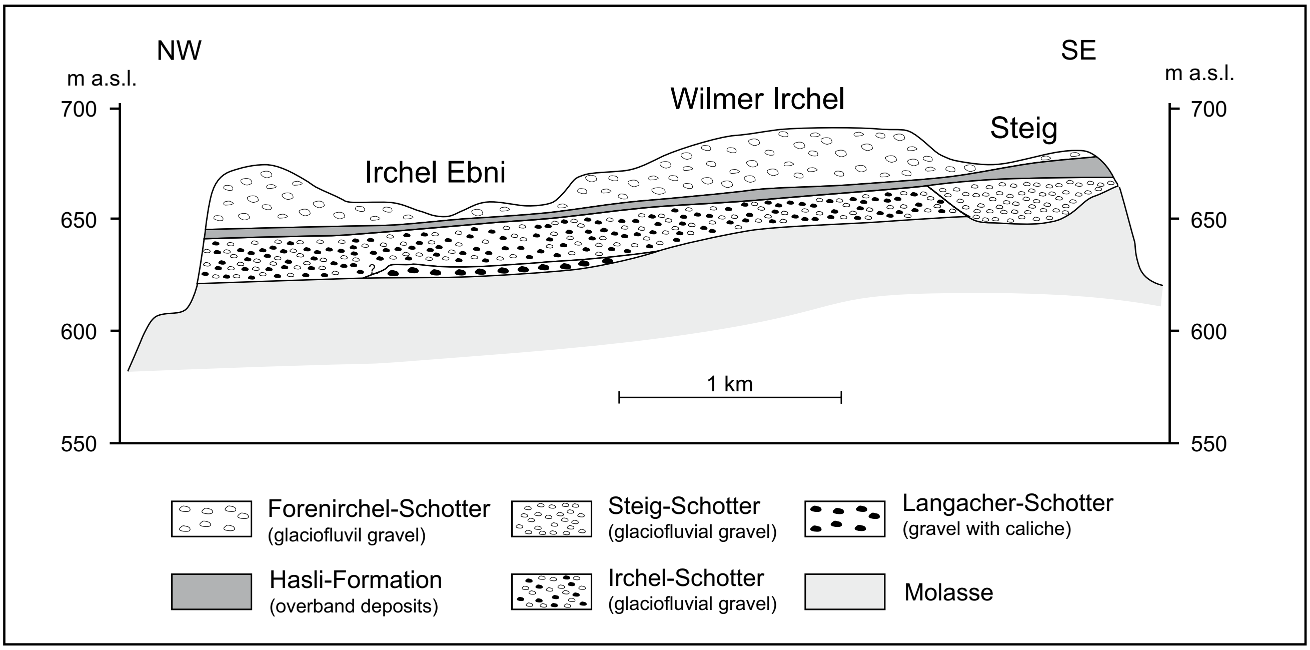

Fig. 3: Geological situation at Irchel ('Höhere Deckenschotter'; modified after Graf *1993).*

Abb. 3: Geologische Verhältnisse am Irchel (Höhere Deckenschotter; modifiziert nach Graf *1993).*

3 Key sites and key regions

3.1 Early Pleistocene ('Deckenschotter glaciations')

The oldest Pleistocene deposits of northern Switzerland, usually referred to as 'Deckenschotter', mainly consist of (glaciofluvial) gravel, with some intercalated glacial sediments (till) and overbank deposits. The present distribution of these deposits is between the easternmost part of the Jura Mountains ('Lägern'), the River Aare, the River Rhine, and Lake Constance (Graf 1993). Lesser remnants of these strata are found to the east of Lake Constance (Graf 2009b) as well as in some parts of northern Central Switzerland (Fig. 2). The remains of 'Deckenschotter' are typically found forming the top of table mountains.

The term 'Deckenschotter' was originally introduced by Penck *&* Brückner (1901/09) for deposits from Bavaria, and refers to past gravel accumulation on a broad-spread plain at the front of Alpine lowland glaciation. The 'Deckenschotter' of northern Switzerland, however, do not represent sheet-like gravel plain deposition on top of Molasse bedrock, but are the fills of several broad channels that are representing the past major drainage network of the northern Swiss Midlands (Graf 1993). 'Deckenschotter' deposits are found at two distinct topographic levels, and are therefore subdivided into a higher ('Höhere Deckenschotter') and a lower ('Tiefere Deckenschotter') unit. Both units represent depositional complexes. The channels of the lower (younger) unit have the same major drainage direction as the higher (older) unit, but are more deeply incised into Jurassic limestone and Molasse bedrock.

3.1.1 Irchel

The Quaternary deposits at Irchel, a tabular hill in northernmost Switzerland (Fig. 1), are a typical example of 'Höhere Deckenschotter' (Graf 1993). The hill reaches for about 5 km from SE to NW, and Pleistocene deposits are found on top of Molasse bedrock, at an elevation between 620 m and 650 m a.s.l., thus about 300 m above the present drainage level.

The Quaternary deposits are subdivided into five units, four of which represent glaciofluvial outwash-gravel (Fig. 3). Petrographical analyses indicate an origin of the sediment from the Walensee-Rhine-System. The oldest unit ('Langacher-Schotter') contains a caliche-type palaeosol in its upper part that is characteristic for Mediterranean to dry-warm climatic conditions. The glaciofluvial gravel on top ('Irchel-Schotter') is cut by a channel-like structure in the SE. This channel is filled by younger glaciofluvial gravel ('Steig-Schotter') showing a prominent difference in petrography compared to the two older units. This implies that erosion was not a local phenomenon but rather indicates reorganisation of the entire drainage network. All over Irchel, the two previous units ('Irchel-Schotter´, ´Steig-Schotter') are covered by overbank and channel fill deposits of a meandering river system, with a thickness between 2 m and 7 m ('Hasli-Formation'). These deposits document a phase of warm environmental conditions of a flood plain. The overbank deposits bear land snails and, of particular importance, vertebrate remains. The presence of *Mimomys* cf. *pliocaenicus*, *M. reidi/pitymyoides*, *Borsodia*, and *Lagurodon*, together with the absence of *Microtus*, is interpreted to indicate a correlation with Mammalian Neogen zone (MN) 17 (Gelasian), representing an age of 2.6–1.8 Ma (Bolliger et al. 1996). The next unit of glaciofluvial gravel ('Forenirchel-Schotter') found on top of the overbank deposits represents the youngest sediments at Irchel.

Although no glacial deposits have been documented at this particular site, such sediments (i.e. till) are found within the younger units of similar deposits of 'Höhere Deckenschotter' farther to the west (Graf 1993). There it

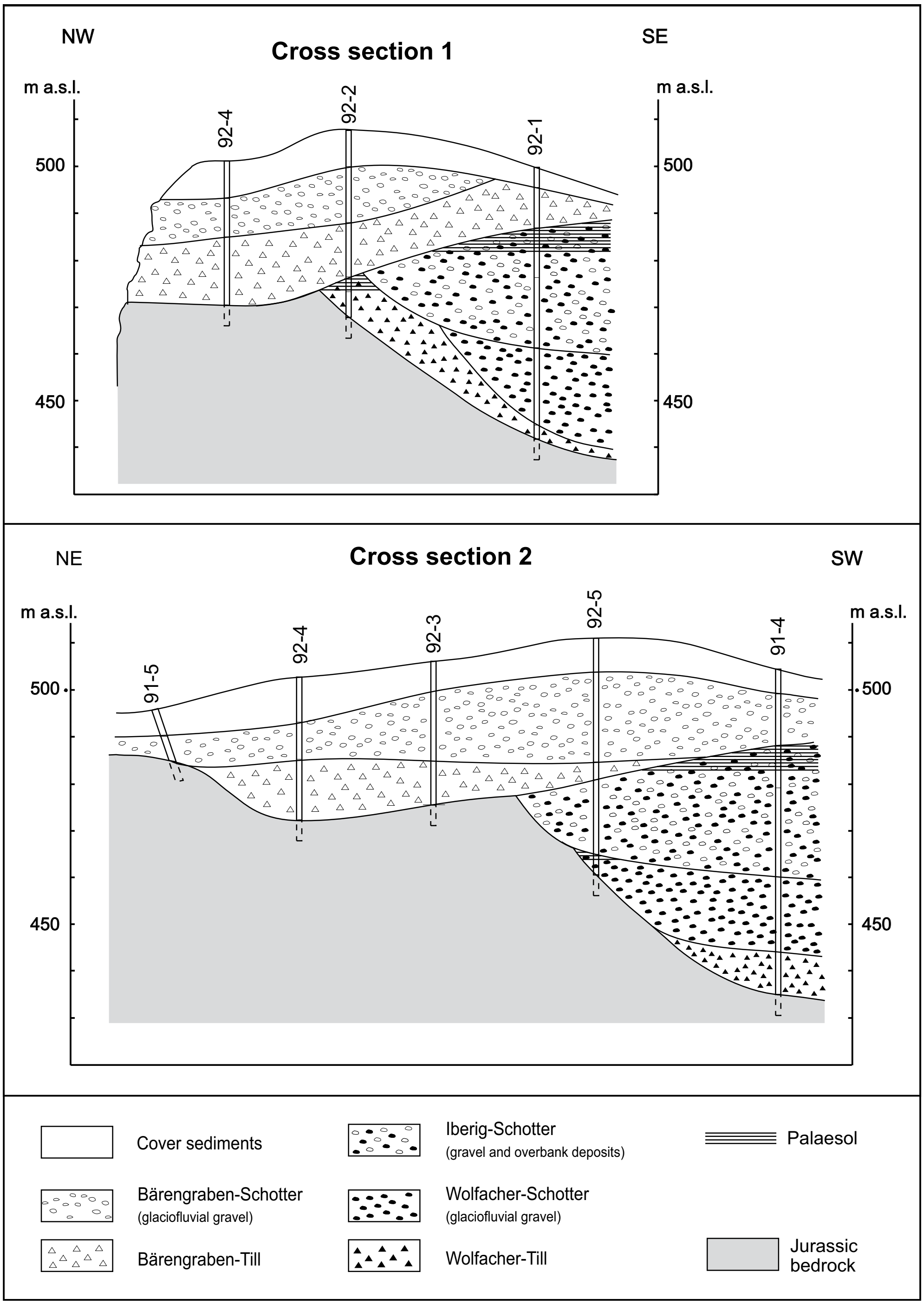

Fig. 4: Geological situation at Iberig ('Tiefere Deckenschotter'; modified after Graf 1993).

Abb. 4: Geologische Verhältnisse am Iberig (Tiefere Deckenschotter; modifiziert nach Graf 1993).

has been shown that at least two units clearly represent phases when alpine glaciers reached far into the eastern part of the Swiss alpine foreland during the Early Pleistocene (considering that the Neogene/Quaternary boundary is now at 2.6 Ma).

3.1.2 Iberig

The deposits at Iberig, a hill in the lower Aare Valley near Würenlingen, are situated at an elevation between 440–470 m a.s.l. (Fig. 1). Topographically this level is significantly lower than the one at Irchel, and therefore the deposits are considered to be part of 'Tiefere Deckenschotter'. Several drill holes revealed the presence of three glaciofluvial and two glacial units at this site (Fig. 4). From gravel petrography it is concluded that the lower till and the lower gravel unit ('Wolfacher-Schotter', 'Wolfacher-Till') are genetically related. The middle gravel unit ('Iberig-Schotter') reveals no petrographic relation to the glacigenic deposits, but the two upper units are again genetically related ('Bärengraben-Schotter', 'Bärengraben-Till'). Interestingly, the uppermost part of 'Iberig-Schotter' includes overbank deposits and palaeosols. This indicates, firstly, that glacial deposition was separated by sedimentation during warmer periods, and, secondly, that the fluvial drainage level remained similar during the glacial and non-glacial times of this period.

A similar threefold subdivision of 'Tiefere Deckenschotter' is found along the River Rhine (Graf 1993), but a fourth gravel unit is found between Lake Constance and Klettgau as well as near Weiach ('Stein-Schotter') (Graf 2009b). This channel system is cut into older deposits and indicates that 'Tiefere Deckenschotter' reflect at least four phases of glaciofluvial deposition, for two of which the presence of glaciers in the Swiss lowlands is clearly documented by the presence of till.

3.2 Middle and Late Pleistocene ('basin glaciations')

Middle and Late Pleistocene deposits outside the glacial limits are typically found as terrace bodies of glaciofluvial gravel along the drainage systems. Morphologically, a major differentiation has been made between the (older) High Terrace, mainly found at elevated positions up to several tens of metres above the valley floor, and the (younger) Low Terrace, usually only a few metres above the present river bed (cf. Kock et al. 2009). In the past, it has generally been assumed that the sediments of the two terrace systems have to be assigned exclusively to the Riss and Würm Glaciation. However, Graf (2009a) has shown that both terrace units comprise sediments deposited during more than one glaciation and the most relevant evidences are summarised below. Interestingly, a complex deposition history of High Terrace aggradation has also been reported for Bavaria (Fiebig & Preusser 2003).

Within the limits of former glaciation extent, the presence of several deep basins and valleys below the sub-surface has been identified by drillings and geophysics, mainly between Lake Constance and the Napf Mountains, but also in the Aare Valley (cf. Preusser et al. 2010). The basal parts of these troughs even reach below sea-level (Keller 1994; Preusser et al. 2010), and the fills mainly consist of glacial sediments. These overdeepened structures are usually interpreted to result from glacial carving, and there is evidence that many of these troughs have been repeatedly occupied and excavated by glaciers during the Middle and Late Pleistocene (Preusser et al. 2010). The multiphase basin archives, accessible only by drilling, have provided major insights into the Quaternary history of the Swiss lowlands, and summaries of the most important archives are given in the following overview.

3.2.1 Möhlinerfeld

Between the villages Mumpf and Rheinfelden, the present River Rhine forms a bend towards the north and bypasses an elevated plateau, known as Möhlinerfeld (Fig. 1). The Pleistocene deposits found here are attributed to the complex of the High Terrace. The surface of bedrock is about 80 m below present land surface, showing a channel-like structure. This reveals that the River Rhine ones flowed straight across Möhlinerfeld. The present course of the river established in the final phase of the penultimate glaciation. From the north, the Wehra Valley, one of the most prominent river valleys draining the Black Forest high plateau to the south, joins the Rhine Valley.

Since Penck & Brückner (1901/09), Möhlinerfeld has been a reference for the so-called Most Extensive Glaciation of the Swiss Alpine foreland (cf. Schlüchter 1988). Originally two individual moraine ridges were distinguished from surface morphology. Recent evidence from the analyses of outcrops and coring revealed that this interpretation is incorrect. The sediments overlying the bedrock are subdivided into several units (Fig. 5), of which the oldest are found in the gravel pit Bünten in the southern part of the area. This unit consists of glacial deposits, a lodgement till with alpine material ('Bünten Till'), representing the advance of an alpine glacier towards this area (Möhlin advance). The till is covered by glaciofluvial gravel ('Bünten-Schotter'), showing an alpine spectrum, but the pebbles and boulders at its base consist of material originating from the Black Forest. In the pit, the uppermost part of the gravel shows intense weathering and this soil is interpreted to reflect interglacial conditions. The following unit is again gravel of alpine origin ('Wallbach-Schotter'), and this and the lower units are deformed by glaciotectonics. Towards the north, another gravel unit ('Möhlinerfeld-Schotter') is found on top of Wallbach gravel with an erosive contact. This gravel is dominated by alpine material but contains boulders and pebbles of Black Forest origin. The boulder horizon probably reflects the erosional remains of an intensively weathered till ('Zeiningen-Till')

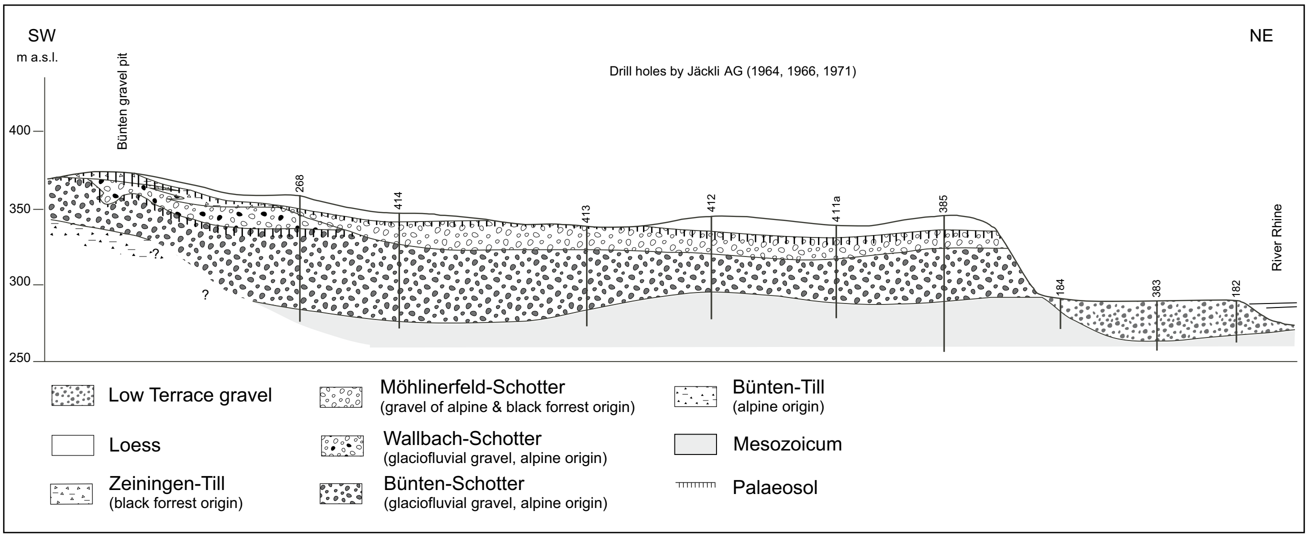

Fig. 5: Geological situation at Möhlinerfeld (Möhlin glaciation; modified after Graf 2009a)

Abb. 5: Geologische Verhältnisse auf dem Möhlinerfeld (Möhlin-Eiszeit; modifiziert nach Graf 2009a).

found in the southern part of the area, outcropping in the Bünten gravel pit. Petrography of this unit indicates an origin from the Wehra Valley, and indicates an advance of the Black Forest Glacier that reached all over Möhlinerfeld, and probably causing deformation of the two oldest gravel units mentioned above. The youngest unit consist of loess deposits with a thickness of up to 10 m.

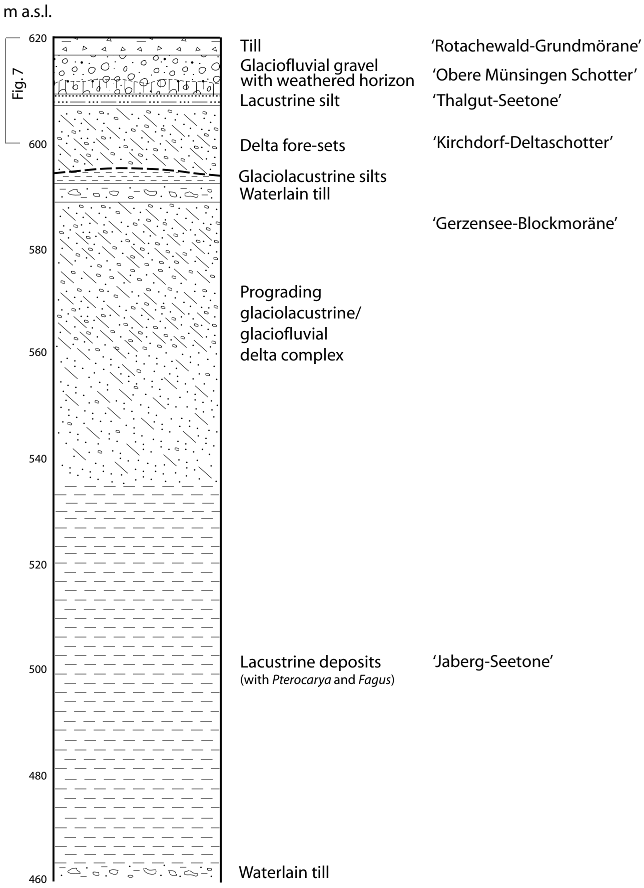

Fig. 6: Geological record of the Thalgut gravel pit and scientific drilling (redrawn after SCHLÜCHTER *1989a,b).*

Abb. 6: Geologische Abfolge in der Kiesgrube und Forschungsbohrung Thalgut (umgezeichnet nach SCHLÜCHTER *1989a,b).*

Despite the fact that the original interpretation of the surface morphology representing two moraine ridges of the Most Extensive Glaciation (PENCK & BRÜCKNER 1901/09) is contradicted by the sedimentological evidence (the ridges are entirely made up of loess), this area represents evidence of the furthest extent of alpine glaciation ('Bünten-Till'), the Möhlin Glaciation.

3.2.2 Aare Valley

This region comprises the middle reaches of the River Aare, i.e. the area between the margin of the Alps at Lake Thun and the narrows near the town of Olten, where the Aare for some part flows through Jurassic limestone (Fig. 1). For this article, evidence from sites in adjacent regions in Seeland, the Jura Mountains and the midlands of Emmental are included in this section.

The sequence in the Thalgut gravel pit (Fig. 1) and its downward extension in a scientifically executed drill hole represent one of the most complex Quaternary succession of the Swiss lowlands (Fig. 6; SCHLÜCHTER 1987a, 1989a, b). The lowest unit reached in the drill hole is composed of glacial sediments deposited in a lake (water-lain till), passing in to lacustrine deposits ('Jaberg Seetone'). The latter unit contains an interglacial pollen assemblage with a dominance of *Fagus* (beech, up to 58 %) and a prominent presence of *Pterocarya* (wingnut, up to 7 %) (WELTEN 1988). The lacustrine deposits are interpreted as bottom-sets and develop into the fore-sets of a prograding delta. In the upper part the fore-sets have a glacial character, as is indicated by the presence of boulders and diamictic, subaquatic mudflows. The top-sets of the delta sequence consist of coarse boulders and are covered by a subaquatically deposited till. The lake basin persisted after ice retreat, as is documented by deposition of laminated sandy silt. These fine-grained sediments are cut by an erosional surface showing a pronounced palaeo-relief. Soil development associated with this discontinuity is interpreted to represent at least one well-developed warm period. Coarse delta gravel was later deposited filling up the existing relief ('Kirchberg-Deltaschotter'), and it is interesting to note that deposition was

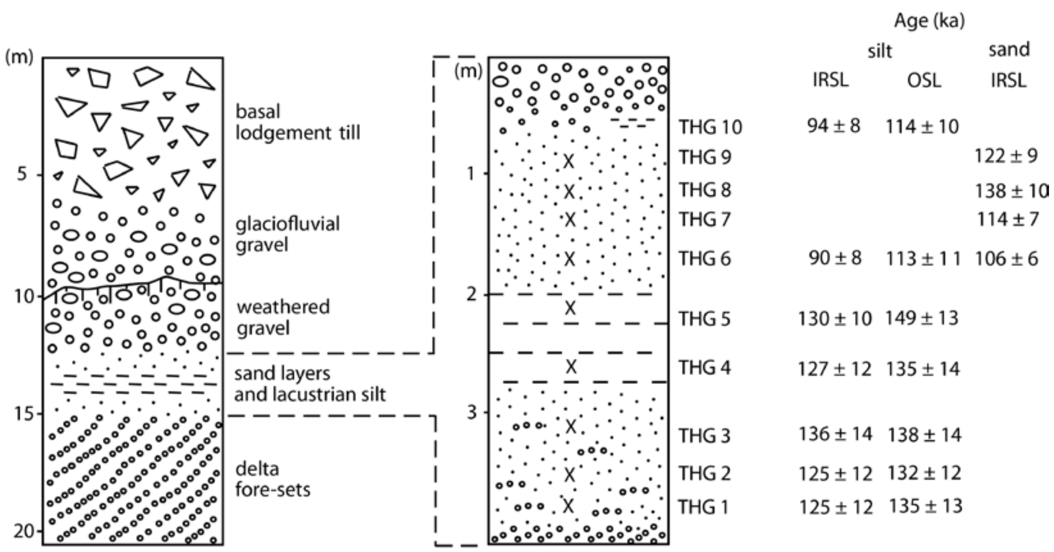

Fig. 7: Upper part of the Thalgut section with luminescence ages (from PREUSSER & SCHLÜCHTER *2004).*

Abb. 7: Oberer Teil des Profils von Thalgut mit Lumineszenzalter (aus PREUSSER & SCHLÜCHTER *2004).*

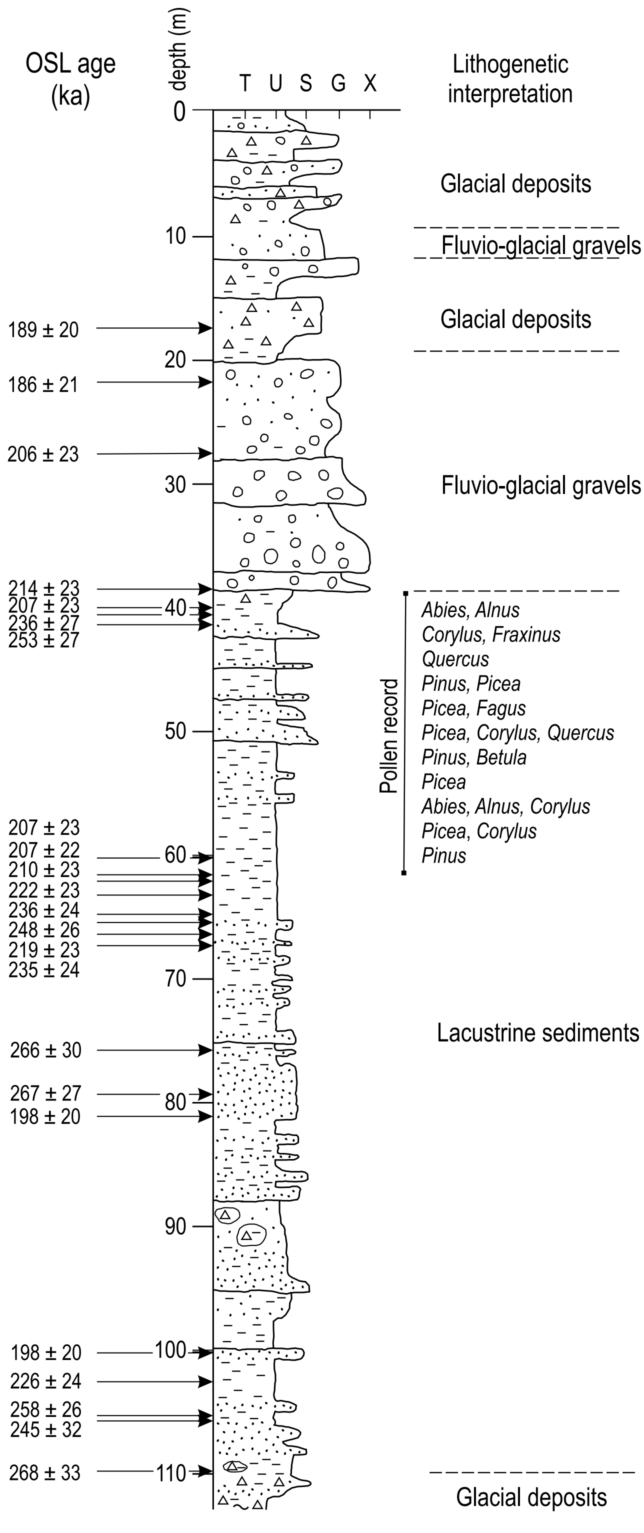

Fig. 8: The geological record of the Meikirch 1981 scientific drilling with OSL ages and major pollen zones (modified after Preusser *et al. 2005).*

Abb. 8: Geologische Abfolge der Forschungsbohrung Meikirch 1981 mit OSL Altern und Hauptpollenzonen (verändert nach Preusser *et al. 2005).*

by a stream almost perpendicular to the present drainage direction. The pebbles are re-worked Molasse bedrock and show few components from the Helvetikum and the Central Alps, implying that the gravel was not deposited by the Rivers Aare, Kander, or Simme. From the sedimentological point of view a close presence of a glacier during deposition appears unlikely. In its upper part, the gravel shows a concordant transition via a sandy layer into silt ('Thalgut Seetone') (Fig. 7). Based on pollen analysis and luminescence dating, this basin deposit is correlated with the Last Interglacial (Eemian) (Welten 1982; Preusser & Schlüchter 2004). In parts of the gravel pit weathered gravel was situated at the top of the basin deposits, mainly eroded during deposition of the next gravel unit ('Obere Münsingen Schotter'). The youngest gravel unit is topped by basal till ('Rotachewald-Grundmoräne), correlated with the Last Glaciation of the area (Schlüchter 1989a, b). The weathered gravel above the basin deposits are, based on the petrography, interpreted to result from a glacier advance beyond the margin of the Alps. The age of this advance has to be younger than Eemian but must be significantly older than the last advance, as it shows intense weathering. Luminescence dating of sandy sediments on top of the interglacial deposits implies that the weathered gravel unit was probably deposited during an early phase of the last glacial cycle (Preusser & Schlüchter 2004).

Another important stratigraphical record of the Aare Valley is the scientific drill hole near Meikirch, north of Bern (Fig. 1). Here, fine-grained lake sediments are found below ca. 40 m of coarse-grained melt water deposits (Fig. 8). The lake sediments (ca. 70 m) are situated on top of glacial deposits (till). Detailed pollen analyses revealed evidence for three warm periods within the lake deposits, separated by two cold phases (Welten 1982, 1988). Based on luminescence dating and re-interpreting the original palynostratigraphy, Preusser et al. (2005) correlate these three warm phases, each of which represents interglacial environmental conditions, with Marine Isotope Stage (MIS) 7 (242–186 ka).

'Höhenschotter', glaciofluvial gravel situated in elevated morphological positions, are considered as the oldest Quaternary deposits of the middle and upper Emmental (Gerber 1941) (Fig. 1). The sediments are found as relicts of partially cemented former channel fills and delta deposits on top of Molasse bedrock (Gerber 1950; Gruner 2001). The gravel is mainly composed of pebbles originating from the Aare Glacier, but also partially contains material derived from the Valais, mainly in the till on top of the glaciofluvial deposits. From its morphological position, sedimentation occurred during a glaciation of greater extent than the Last Glaciation, and has been considered to be older than Eemian. This minimum age estimate is supported by U/Th dating of calcite precipitates from the Landiswil gravel pit (Dehnert et al. 2010). Infrared stimulated luminescence (IRSL) dating of sandy parts of the delta deposits at the same site gave two ages of 153 ± 16 ka and 160 ± 14 ka (Dehnert et al. 2010).

In the Jura Mountains, erratic boulders are found outside the limits of the Last Glaciation. Without any age control, these deposits have been tentatively correlated with either the Rissian Glaciation of Penck & Brückner (1901/09) or the Most Extensive Glaciation, thought to be older than 700 ka (Schlüchter & Kelly 2000). A first study applying ^{10}Be and ^{21}Ne surface exposure dating to four selected boulders from the Montoz anticline resulted in ages between ca. 70 ka and 170 ka (Graf et al. 2007). The younger ages of this data set were determined from two boulders of smaller size that had probably rotated in the past. As a consequence, Graf et al. (2007) consider it more likely that the larger boulders reflect the age of deposition. Using a conservative

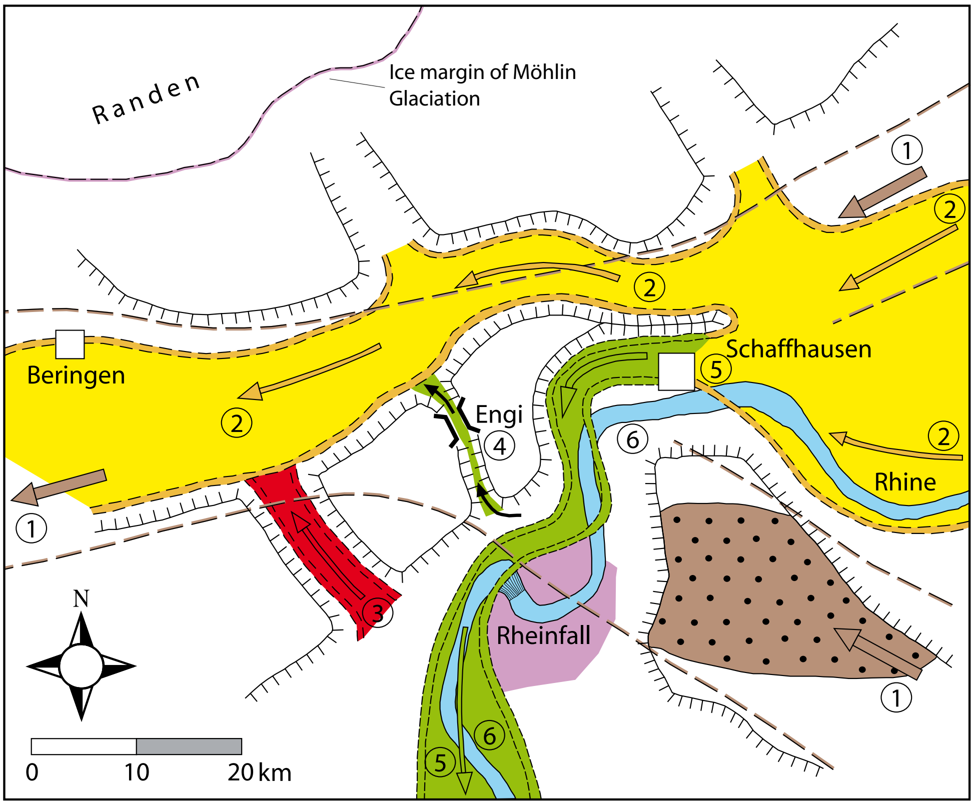

Fig. 9: Pleistocene troughs in the area Schaffhausen-Klettgau (modified after Keller & Krayss 2010). 1: Upper Klettgau trough ('Tiefere Deckenschotter'), 2: Main Klettgau trough (Möhlin to Habsburg), 3: Neuhauserwald trough (Habsburg to Beringen), 4: Engi trough (Beringen, Birrfeld maximum), 5: Rheinfall trough (late Beringen to Birrfeld), 6: Present Rhine trough (since late Birrfeld).

Abb. 9: Pleistozäne Rinnen im Raum Schaffhausen-Klettgau (modifiziert nach Keller & Krayss 2010). 1: Obere Klettgau Rinne (Tiefere Deckenschotter), 2: Klettgau Hauptrinne (Möhlin bis Habsburg), 3: Neuhauserwald Rinne (Habsburg bis Beringen), 4: Engi Rinne (Beringen, Birrfeld Maximum), 5: Rheinfall Rinne (spätes Beringen bis Birrfeld), 6: Heutige Rinne des Rheins (seit spätem Birrfeld).

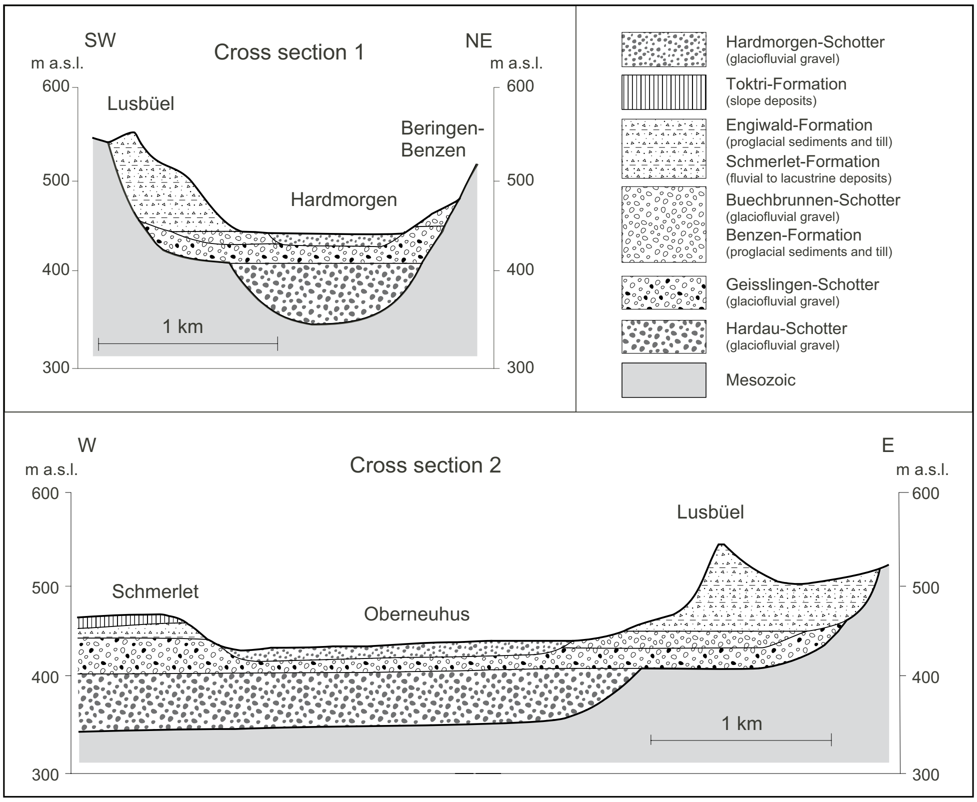

Fig. 10: Two cross sections through the Klettgau Valley (modified after Graf 2009a).

Abb. 10: Zwei Querschnitte durch das Tal des Klettgau (modifiziert nach Graf 2009a).

erosion rate of 3.0 ± 0.5 mm a^{-1} results in age estimates of 143 ± 17 ka (^{10}Be) and 124 ± 12 ka (^{21}Ne), and of 163 ± 21 ka (^{10}Be) and 138 ± 13 ka (^{21}Ne), respectively.

The gravel pit Finsterhennen is situated in the western part of the Aare Valley, also known as Seeland (Fig. 1). Exposed in this pit are till and pro-glacial meltwater deposits attributed to the Last Glaciation of the Swiss lowlands. The radiocarbon age of a mammoth tusk of 25'370 ± 190 ^{14}C yr (29'650-30'640 cal. BP) from the middle part of the glaciofluvial sediments is confirmed by Optically Stimulated Luminescence (OSL) ages of 28.5 ± 2.3 ka and 28.9 ± 2.5 ka (Preusser et al. 2007). Interestingly, OSL dating of glaciofluvial sediments from below a residual till in the lower part of the exposure gave an age of 76 ± 6 ka, indicating an ice advance of the Valais Glacier to this point during late MIS 5 or early MIS 4.

Near the village Wangen an der Aare, two separated terminal moraine ridges are present, known as older and younger Wangen stage. The inner and hence younger stage has traditionally been correlated with the Last Glaciation and this assumption is confirmed by surface exposure dating of a large boulder near Steinhof (Fig. 1), giving a mean age of 20.1 ± 1 ka (Ivy-Ochs et al. 2004). The age of the outer ridge is not known but loess-like cover sediments on top of the glacial deposits indicate that the glaciation responsible for the formation of the ridge has to be older than the Last Glaciation (Mailänder & Veit 2001). However, whether this represents an early Late Pleistocene glacial advance (e.g. MIS 4), an equivalent of MIS 6, or an even older glaciation, remains to be investigated.

3.2.3 Klettgau

The present dry valley of Klettgau (Fig. 1) was during most of the Pleistocene part of the Rhine Valley before the river changed its course towards the south near the city of Schaffhausen (Fig. 9). Relicts of 'Tiefere Deckenschotter' and some minor remnants of 'Höhere Deckenschotter' are found in marginal parts of the valley. From gravel petrography these deposits indicate an origin from the Lake Constance-Rhine Glacier system, and document the active course of the River Rhine during most of the Pleistocene. The sediments of the valley bottom represent High Terrace deposits from the morphological point of view (Graf 2009a).

The channel of Oberklettgau, with a base at 340 m a.s.l., contains a complex sedimentary fill (Fig. 10). The sequence starts with glaciofluvial sediments ('Hardau-Schotter') that reach a thickness of up to 150 m. The gravel originates from the Lake Constance-Rhine Glacier, although the presence of ice in Klettgau is not documented for the time of gravel formation (Graf 2009a). An erosional trough was later incised into the gravel down to a level of 410 m a.s.l. In addition to the erosion along the valley axis, another channel originating from the south incised at the same time. This trough was later filled by glaciofluvial gravel ('Geisslingen-Schotter'), with deposition in the eastern part originating from the Lake Constance-Rhine glacier, and in the southern channel from the Walensee branch of the Rhine glacier. The maximum ice extent during this phase (Hagenholz advance) was about 25 km SE of Klettgau, close to the present airport of Zurich (Graf 2009a).

The following phase of sedimentation (Beringen Glacial) is characterised by the direct presence of glaciers in Oberklettgau. The presence of the two branches of Rhine glacier (Lake Constance, Walensee) in the region is evidenced by petrography of the gravel. The ice reached towards the present village of Löhningen and left tills in the marginal areas of Oberklettgau, fluvial sand and gravel down-valley, and fine-grained sediments in smaller side valleys ('Buechbrunnen-Schotter' and 'Benzen-Formation'; Fig. 10). Sedimentary evidence reveals that the glaciation comprises two advances separated by a phase of ice retreat. First results of IRSL dating imply an age of ca. 150 ka for the first ice advance towards the Klettgau (Preusser & Graf 2002; Graf 2009a). Glaciers left complex sedimentary successions in the Rhine trough and the southerly channel, comprising till, lake deposits and gravel ('Engiwald-Formation' and 'Schmerlet-Formation'), was not eroded during ice meltdown. Partial erosion in Oberklettgau was caused by meltwater flowing through a small valley (Engi). Later, meltwater discharge shifted to the south, causing initial incision of the present course of the River Rhine. This newly formed erosional channel was later, probably during a temporal re-advance within general ice retreat, filled with 60 m of glaciofluvial gravel ('Schaffhausen-Schotter'). The mean IRSL age for this unit is about 130 ka (Preusser & Graf 2002; Graf 2009a). The above mentioned small valley was again used by meltwater during the maximal ice extent of the Last Glaciation, causing the deposition of 10 m gravel ('Hardmorgen-Schotter') in Oberklettgau.

3.2.4 Birrfeld

Located in the lower Reuss Valley, Birrfeld is bounded by Molasse hills in the east and west, by the Mesozoic Lägern structure to the north, and by the hills of Habsburg to the NE (Fig. 1). Bedrock surface is characterised by an overdeepened basin to the south of the Lägern and by two channels heading northward across the Mesozoic structure, all of which are attributed to subglacial erosion (Graf 2009a). To the NW of Birrfeld, a palaeo-channel turns below the hill of Habsburg from SW to N. The Habsburg palaeo-channel contains the oldest sediments of the region, comprising lacustrine sediments and till, probably reflecting deposition during the Möhlin advance. On top are up to 100 m thick gravel deposits ('Habsburg-Schotter'), intercalating with glacial sediments and subglacial gravel in the southern part of the basin (Fig. 11). These deposits are attributed to the Habsburg glaciation.

The next phase of accumulation is documented by glacial deposits and basin sediments. This Remigen advance of the Beringen glaciation reached far beyond Birrfeld and formed two channels crossing the Lägern structure. Glacial ('Hausen-Till') and associated proglacial gravel ('Remigen-Schotter') deposits of this advance are found on top of 'Habsburg-Schotter' (Fig. 11). The two channels contain basin sediments in glaciolacustrine ('Hausen-Lehm', Fig. 11) and partially in sandy facies ('Reusstal-Sand', Fig. 12). 'Lupfig-Schotter', found in channels incised into the basin sediments in the western part of the region, is interpreted to represent a re-advance during the meltdown phase of the Remigen advance. This unit is covered by a well-developed palaeosol (Fig. 12), which may represent the Last Interglacial.

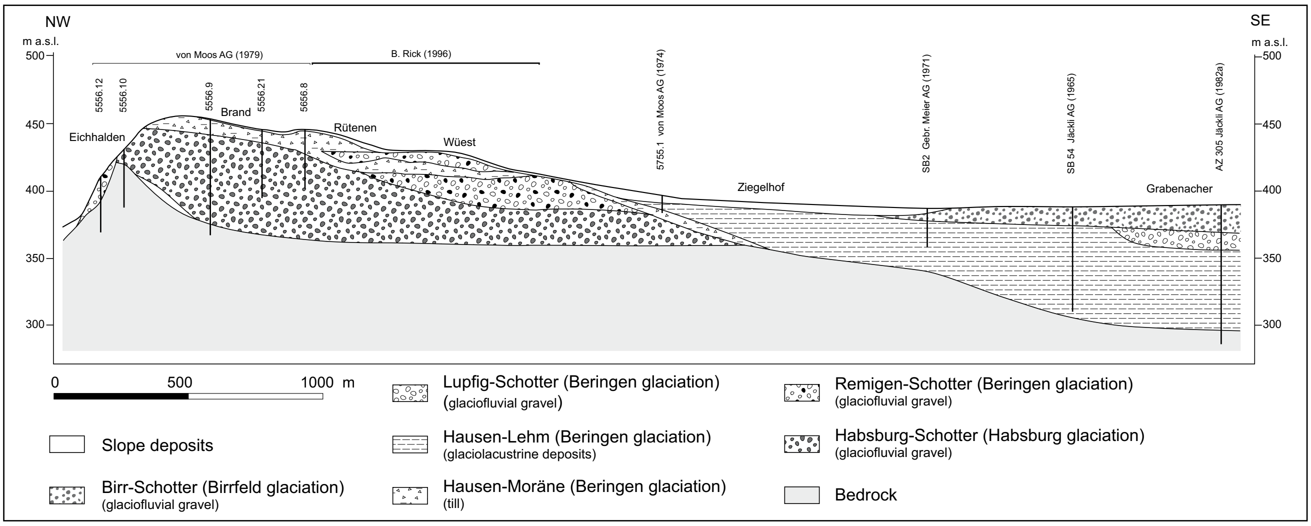

Figure 11: Geological situation in the surroundings of Habsburg hill (modified after Graf *2009a).*

Abbildung 11: Geologische Verhältnisse im Umfeld des Habsburgs Hügels (modifiziert nach Graf *2009a).*

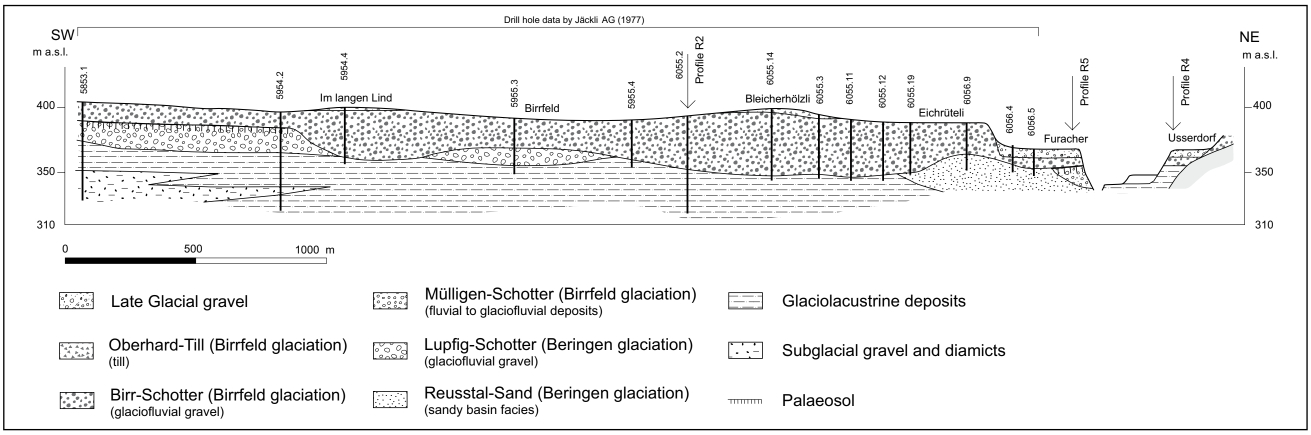

Fig. 12: Geological situation at Birrfeld (modified after Graf *2009a)*

Abb. 12: Geologische Verhältnisse im Birrfeld (modifiziert nach Graf *2009a).*

Along the slopes of the present Reuss Valley, fluvial deposits changing into glaciofluvial sediments ('Mülligen-Schotter') on top of 'Reusstal-Sand' have been dated by IRSL to 73 ± 11 ka and 55 ± 14 ka (Preusser & Graf 2002). This glacial ice advance, however, did not reach Birrfeld. The gravel bears a weakly developed palaeosol.

The first advance of the Last Glaciation is mainly documented by glacial deposits along the present Reuss Valley (Lindmühle advance). After temporal ice retreat glaciofluvial gravel forming the present land surface has been deposited ('Birr-Schotter', Fig. 11, Fig. 12). This unit is partly found on a paleosol developed on the gravel of the Beringen glacial ('Lupfig-Schotter'), and intercalates with glacial deposits that partly formed flat hills of till ('Oberhard-Till', Fig. 12). Different stages of ice meltdown are represented by thin gravel units along the Reuss Valley (Fig. 12).

3.2.5 Linth Basin

The 15 km long and 7 km wide Linth Basin is located directly at the margin of the Alps, and spreads towards the north from the junction of Walensee and Linth Valley (Fig. 1). Two Molasse inselbergs subdivide the Linth Plain between Walensee and Lake Zurich. Older glacial deposits are long known from Buechberg and Kaltbrunn (Brockmann-Jeroch 1910; Jeannet 1923; Welten, 1988). In his compilation of the Quaternary of the Linth area Schindler (2004) describes the sedimentary sequences in detail, and it is interesting to note that he refers to two independent 'Riss' glaciations. A summary of the sedimentary sequence of Buechberg and Kaltbrunn-Uznach is given in Figure 13, and the presence of lacustrine deposits at the same altitude is important for correlation between the two outcrops.

During the oldest preserved glaciation, the Linth Glacier carved out a substantial basin into Molasse bedrock at the northern margin of the Alps. According to the drill hole at Tuggen, the surface of bedrock in the middle of that basin is probably at a depth of about 100 m a.s.l. (Schindler 2004). During meltdown of this glaciation a lowermost till was deposited and a lake subsequently developed, in which delta sediments have been deposited ('Günterstall Deltaschotter'). The sediments were derived from local streams and the interglacial character of deposition is documented by plant macro remains (Brockmann-Jerosch 1910). The delta is cut by till

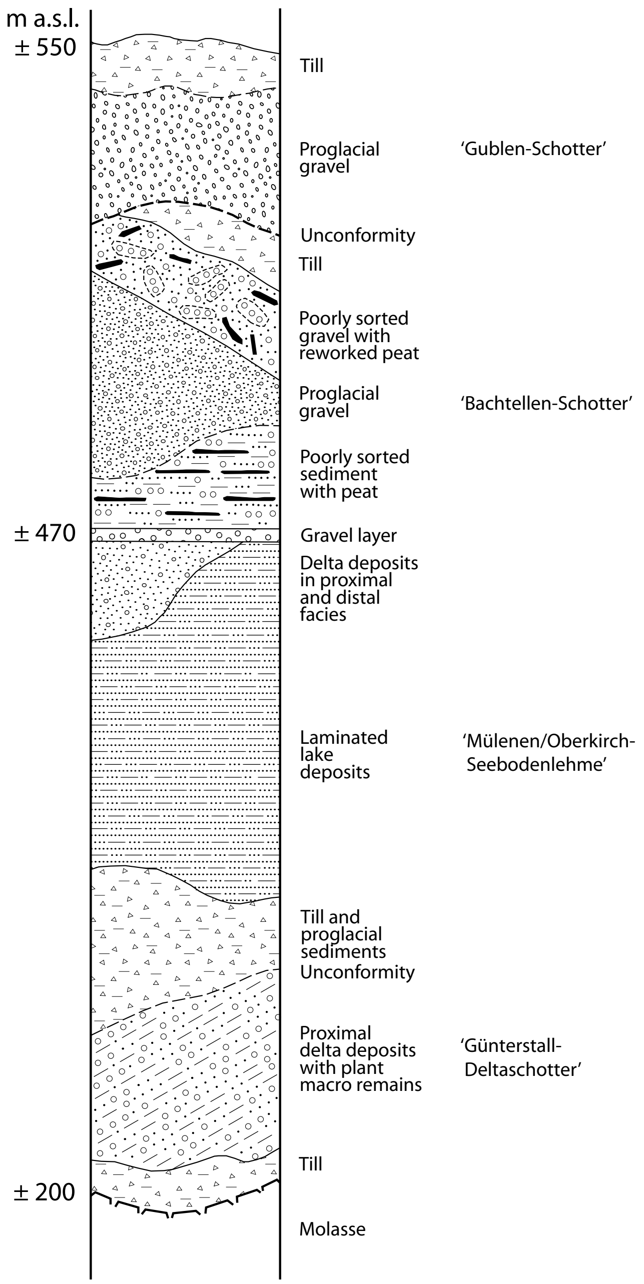

Fig. 13: Geological composite section of the Linth Basin (modified after Keller & Krayss 2010).

Abb. 13: Geologisches Sammelprofil der Linthbecken (modifiziert nach Keller & Krayss 2010).

documenting a next glacial advance into the Linth Basin. The till reaches a thickness of up to 50 m and its base has been found in drilling down to a depth of 300 m a.s.l., indicating deep erosion in the central part of the basin. Laminated grey lake deposits then follow and reach a thickness of up to 150 m, as found in drill holes up to 100 m below the present surface of the Linth Plain. They are found over a distance of more than 30 km from Buechberg to the middle reaches of Walensee. In its upper parts, the lake deposits bear plant remains and pollen of boreal trees and *Alnus* (alder), indicating that the lake represents a late glacial period of a preceding glaciation (Welten 1988). The lake deposits are overlain by a horizontal gravel layer, indicating a lake surface at 470 m a.s.l. In the western part of Buechberg, delta deposits with pebbles originating from the Linth Glacier catchment are found within the lake deposits.

The next higher unit ('Bachtellen-Schotter') shows a coarsening upwards tendency and partially non-orientated deposition and disturbances. The unit is interpreted to represent an ice-marginal position and proglacial sediments of an ice-advance. Above an unconformity, unsorted gravel and sand follow with irregularly admixed pieces of peat and gravel layers, the later originating from the unit beneath. These deposits likely represent sediments reworked by an advancing glacier. Lodgement till, although not present in all outcrops, documents that the region was overrun by the Linth Glacier during this advance. A pronounced unconformity on top of the till is probably of an erosional nature and likely reflects interglacial conditions. The next glacial advance is documented by coarsening upward ice-marginal gravel deposits ('Gublen-Schotter') that are erosionally cut and covered by till. The latter, uppermost unit continuously covers the valley flanks and inselbergs of the Linth Basin and is supposed to represent the Last Glaciation of the area.

3.2.6 Glatt Valley

The lower Glatt Valley spreads over 40 km from the Molasse ridge of Hombrechtikon (near Rapperswil at Lake Zurich) via Kloten and Bülach to the River Rhine (Fig. 1). Beside some hills made up by Molasse, the entire valley is characterised by outcropping deposits of the Last Glaciation. A series of drill holes gave insights into the composition of the Quaternary basin fills of this region. Glatt Valley is a typical overdeepened foreland basin with bedrock altitudes of 200–300 m a.s.l. in the eastern main branch, and ca. 350 m a.s.l. in the small western branch. The occurrence of older basin deposits is along the main branch of the trough between Greifensee and Pfäffikersse (Fig. 1) (Haldimann 1978; Wyssling & Wyssling 1978; Welten 1982; Kempf 1986; Wyssling 2008; Graf 2009a)

The composite sketch of the basin fills (Fig. 14) shows that the sediment succession in the main basin is subdivided by a prominent unconformity into a central and a western part. Besides the main basin, the sub-basins of Greifensee and Pfäffikersee are found to the west and east, respectively. The main basin (Fig. 14) has a bedrock depth of about 300 m a.s.l. in the middle part of Glatt Valley, and reaches as low as 250 m a.s.l. The bottom of the trough is filled by till and partially covered by ice-decay meltwater deposits. All over the central parts of Glatt Valley, laminated lake sediments with a thickness of 100–150 m on top of the till are interpreted to represent varved late glacial deposits. Along the central basin axis between Greifensee and Pfäffikersee gravel deposits occur that reach a thickness of 30 m and are partially cemented ('Aathal-Schotter'). These sediments are exposed in the Aa Valley but have also been found in drillings farther north, up to the village of Kloten. Plant remains and debris of snails found in the basal part of the gravel imply a warm period preceding the deposition of the gravel. In its upper part, the gravel contains lenses of till that are interpreted to represent an advancing glacier. The unit is expected to represent proglacial sediments because it is actually covered by till. An unconformity docu-

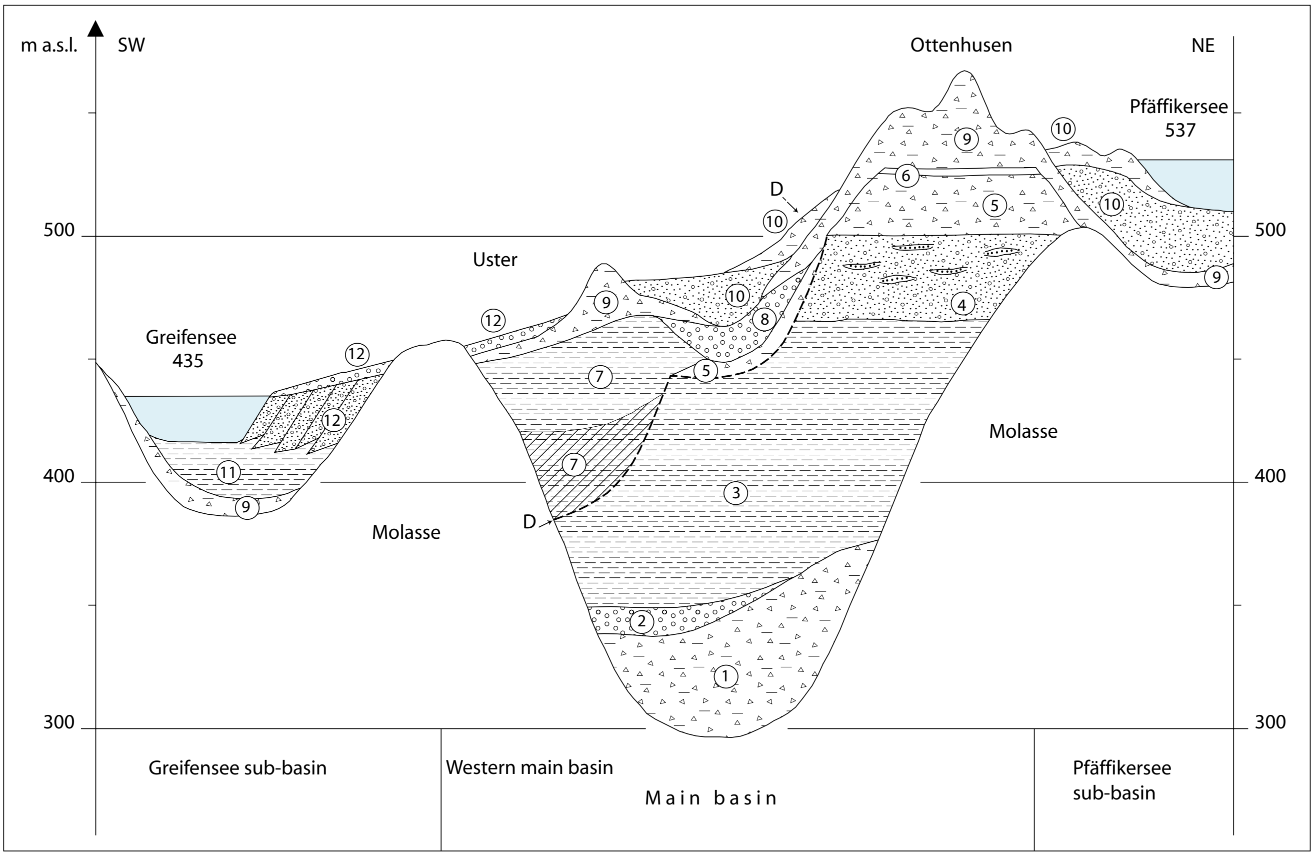

Fig. 14: Geological cross section of the Upper Glatt Valley (modified after Graf *2009a and* Keller *&* Krayss *2010). 1: Till, 2: meltwater deposits, 3: laminated lacustrine sediments, 4: pro-glacial gravel; basal part bearing plant remains; upper part containing lenses of till; 'Aathal-Schotter', 5: till, 6: unconformity, 7: lake sediments; basal part bearing plant remains, 8: gravel, 9: till, 10: gravel and till of the final phase of the Last Glaciation, 11: lake sediments, 12: post-glacial deposits.*

Abb. 14: Geologisches Querprofil durch das obere Glatttal (modifiziert nach Graf *2009a und* Keller *&* Krayss *2010) 1: Till, 2: Schmelzwasserablagerungen, 3: laminierte Seesedimente, 4: Vorstossschotter; mit Pflanzenresten im basalen Teil; Linsen von Till im oberen Teil, 'Aathal-Schotter', 5: Till, 6 : Diskordanz, 7: Seesedimente; Pflanzenreste im basalen Teil, 8: Schotter, 9: Till, 10: Schotter und Till der finalen Phase der letzten Vergletscherung, 11: Seesedimente, 12: Postglaziale Ablagerungen.*

mented by sand and silt separates this lower from an upper till unit attributed to the Last Glaciation.

The western main basin (Fig. 14) is characterised by a deep-reaching unconformity, cutting the upper part of the lake sediments. It is partly covered by till and indicates glacial erosion of the trough. The western part of the basin comprises lake sediments rich in plant remains and bearing Eemian pollen assemblages (Welten 1982). The lake deposits are mainly covered by gravel and till of the last glacial advance, but at Gossau (Fig. 1) a complex succession of the early and middle part of the Birrfeld glaciation had been exposed (Schlüchter et al. 1987). Luminescence dating indicates that delta deposits at Gossau, interpreted to result from a glacial advance, where deposited at the very beginning of the Birrfeld glaciation, c. 105 ka ago (Preusser 1999; Preusser et al. 2003). Till of the Last Glaciation is found in the basal and western part of Greifensee sub-basin. Sediments in the Pfäffikersee sub-basin and in the highest parts of the main basin indicate that the glacier re-advanced over the previously deposited gravel and sand during the final phase of the Last Glaciation (Stein am Rhein/Zurich stadial), after temporal ice meltdown. On top of late to post glacial lake sediments a delta was deposited in Greifensee originating from the Aa Valley and Pfäffikersee.

3.2.7 Rafzerfeld/Thur Valley

The River Thur flows in a wide valley from east to west and is a tributary of the River Rhine. Beyond the confluence of both rivers, Rafzerfeld is the continuation of the Thur Valley, at a slightly higher altitude, but the structure is almost perpendicularly cut by the Rhine Valley (Fig. 15). Since the mid-20th century several drill holes have brought new insights into the subsurface stratigraphy of this basin area (Müller 1996; Graf 2009a). It is interesting to note that an overdeepened valley reaches from the Thur Valley to the River Rhine, with a NW orientated branch. The deepest parts of this palaeo-channel reach down to sea-level. The sedimentary fill of this trough, however, apparently only comprises sediment accumulation during the Last Glaciation.

Surface relief is characterised by prominent moraine ridges and extended out-wash plains with several gravel pits allowing access to near-surface sediments (Fig. 15). The region is therefore well suited to investigate the landforming processes along the western front of the former Rhine Glacier (Keller & Krayss 2005a, b; Keller 2005). Ice marginal positions during the Last Glaciation show that the Thur Valley lobe reached Rafzerfeld (Fig. 15), causing the accumulation of out-wash deposits in the area dated

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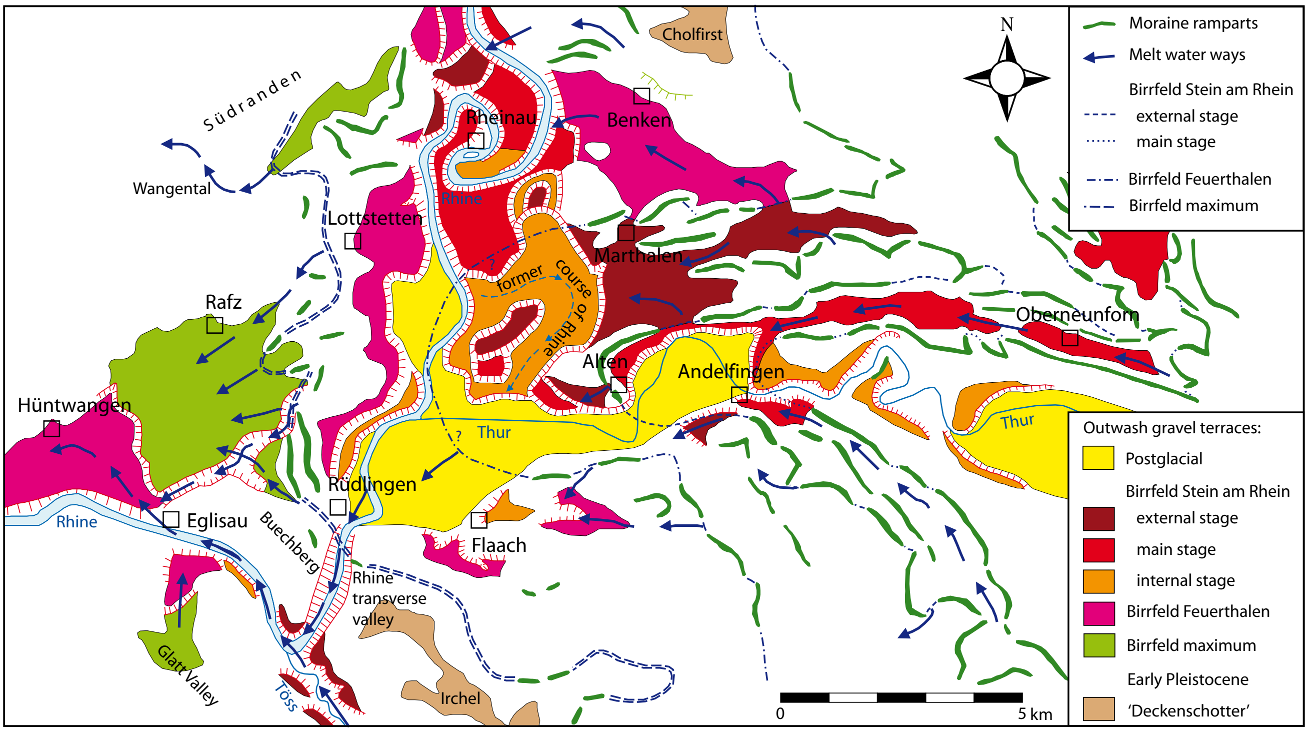

Fig. 15: Geological map of the confluence region of Rivers Rhine and Thur (modified after Keller *2005).*

Abb. 15: Geologische Karte der Konfluenzregion von Rhein und Thur (modifiziert nach Keller *2005).*

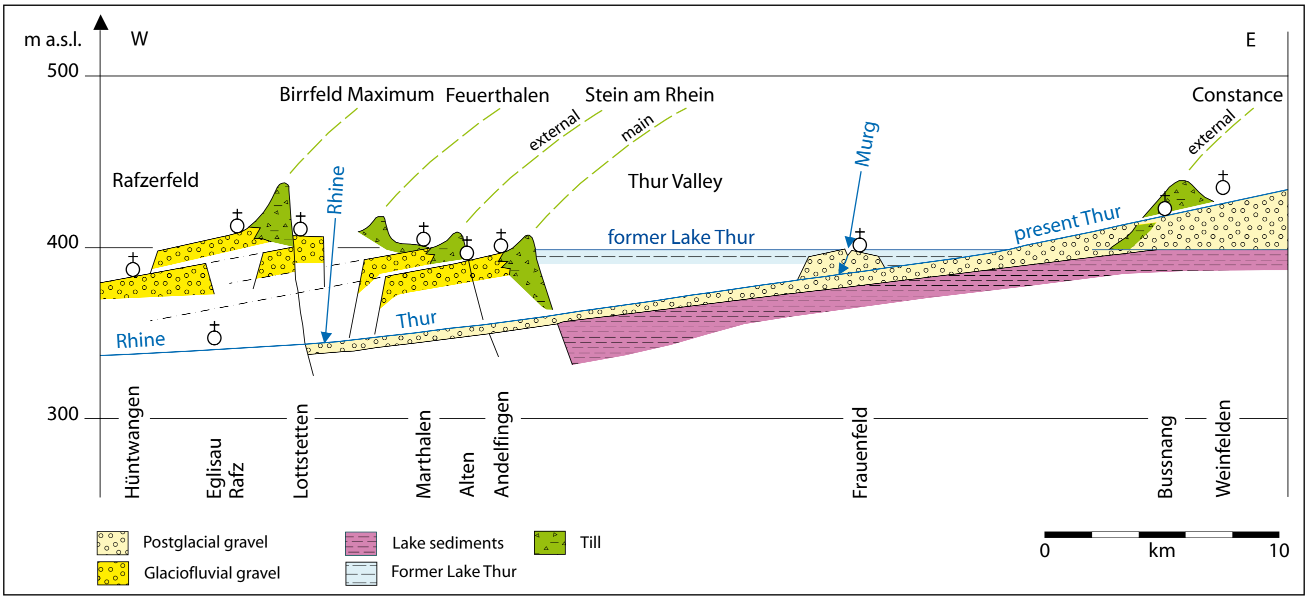

Fig. 16: Geological longitudinal profile of the lower Thur Valley with the location of different ice marginal positions (modified after Keller *&* Krayss *1999).*

Abb. 16: Geologisches Längsprofil durch das untere Thurtal mit der Position verschiedener Eisrandlagen (modifiziert nach Keller *&* Krayss *1999).*

by both OSL and radiocarbon to being just older than ca. 25 ka (Preusser et al. 2007). Aggradation was so prominent that part of the meltwater spilled over into the Töss Valley. When this drainage became dominant, the River Rhine cut the valley of Rüdlingen-Tössegg into molasse bedrock, and Rafzerfeld finally dried.

With the step-by-step meltdown of the Thur Valley lobe, new outwash plains were established, while the River Rhine was cutting deeper and forming several terrace levels. The terrace levels can be correlated to individual terminal moraine ridges, with lower terrace levels being related to more internal ice marginal positions.

During a re-advance of the Thur Valley lobe, particularly well developed terminal moraine ridges were formed close to the present village of Andelfingen (Stein am Rhein stadial), followed by a more-or-less continuous meltdown towards the Lake Constance basin. In the Thur Valley, a 40 km long lake established beyond the terminal moraine ridge near Andelfingen (Fig. 16). Due to further deepening of the Rhine Valley between Rüdlingen-Tössegg and the huge sediment input from the hinterland, the lake disappeared after a few thousand years (Keller & Krayss 1999). The ice-marginal position of Rhine-Linth Glacier has been mapped in detail and reconstructed as three-dimensional ice bodies following glacio-geological aspects (Keller & Krayss 2005a). Based on a substantial number of radiocarbon ages for the different ice-marginal positions, the spatial-temporal ice build-up and, in particular, meltdown have been reconstructed for the Last Glaciation (Fig. 17; Keller & Krayss 2005b).

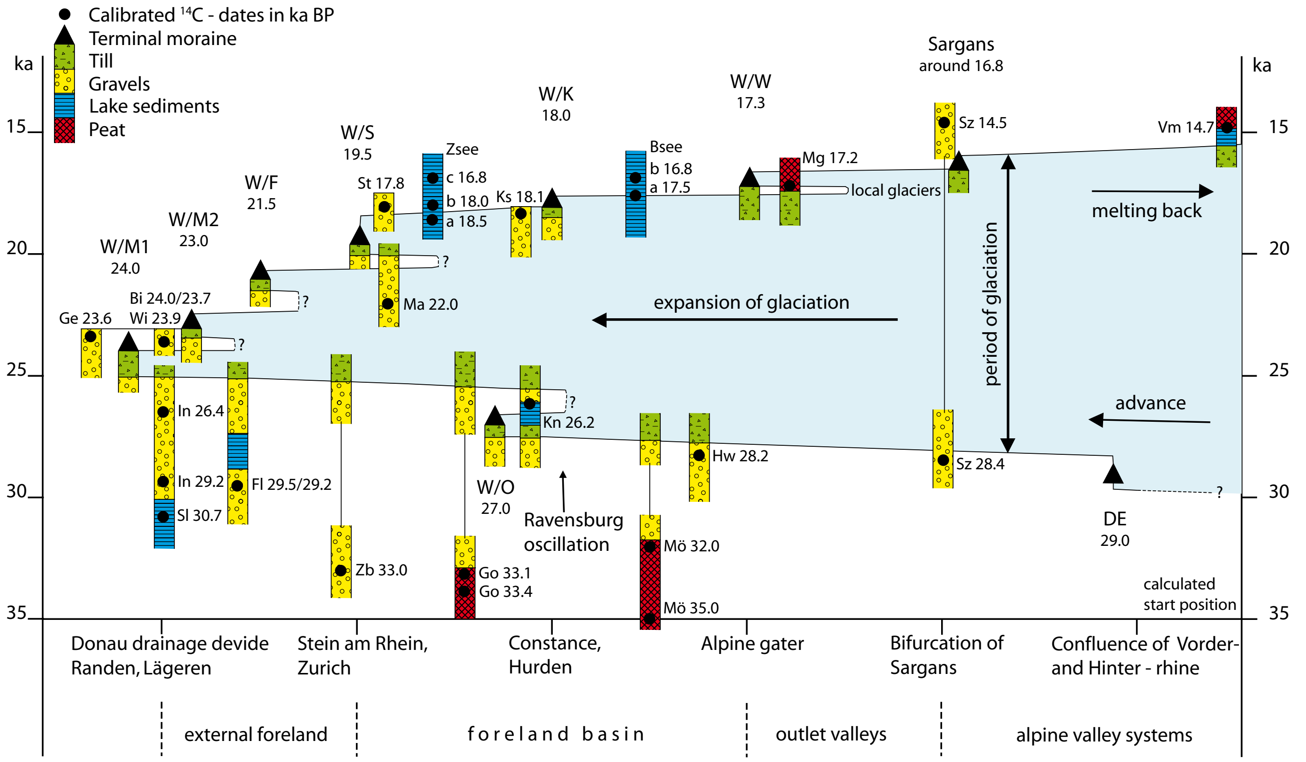

Fig. 17: Chronology of the last glacial advance of the Rhine-Linth glacier (Birrfeld/Würm; redrawn after Keller & Krayss 2005b). Ice marginal positions: DE = Domat-Ems, W/O = Obersee, W/M1 = outer Maximum, W/M2 = inner Maximum, W/F = Feuerthalen, W/S = Stein am Rhein, W/K = Konstanz, W/W = Weissbad.

Abb. 17: Chronologie des letztglazialen Eisaufbaus des Rhein-Linth Gletschers (Birrfeld/Würm; umgezeichnet nach Keller & Krayss 2005b). Eisrandlagen: DE = Domat-Ems, W/O = Obersee, W/M1 = äusseres Maximum, W/M2 = inneres Maximum, W/F = Feuerthalen, W/S = Stein am Rhein, W/K = Konstanz, W/W = Weissbad.

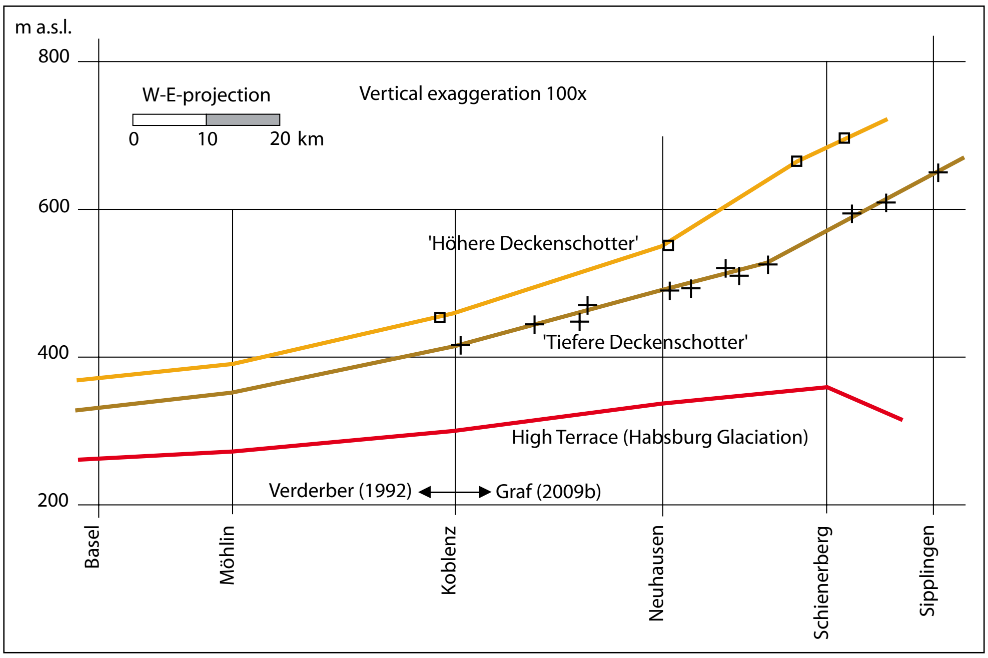

Fig. 18: Base level of gravel beds along the Hochrhein (re-drawn after Keller & Krayss 2010).

Abb. 18: Schotterbasis am Hochrhein (umgezeichnet nach Keller & Krayss 2010).

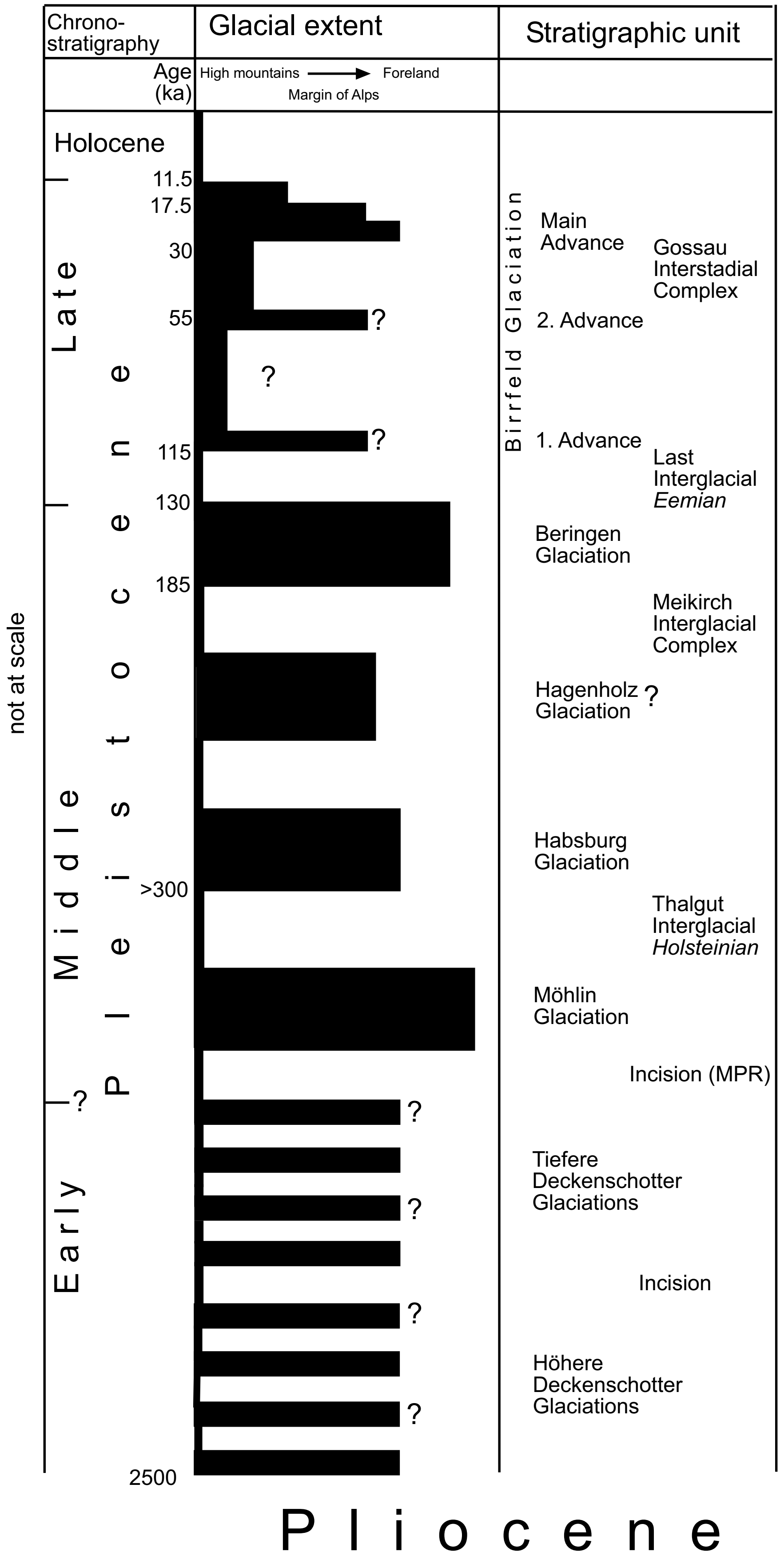

Fig. 19: Stratigraphy scheme showing the glaciation history of Switzerland. According to Keller & Krayss (2010), Hagenholz may represent an early phase of the Beringen Glaciation.

Abb. 19: Stratigraphisches Schema der Vergletscherungsgeschichte der Schweiz. Nach Keller & Krayss (2010) könnte die Hagenholz Eiszeit einer frühen Phase der Beringen Eiszeit. entsprechen.

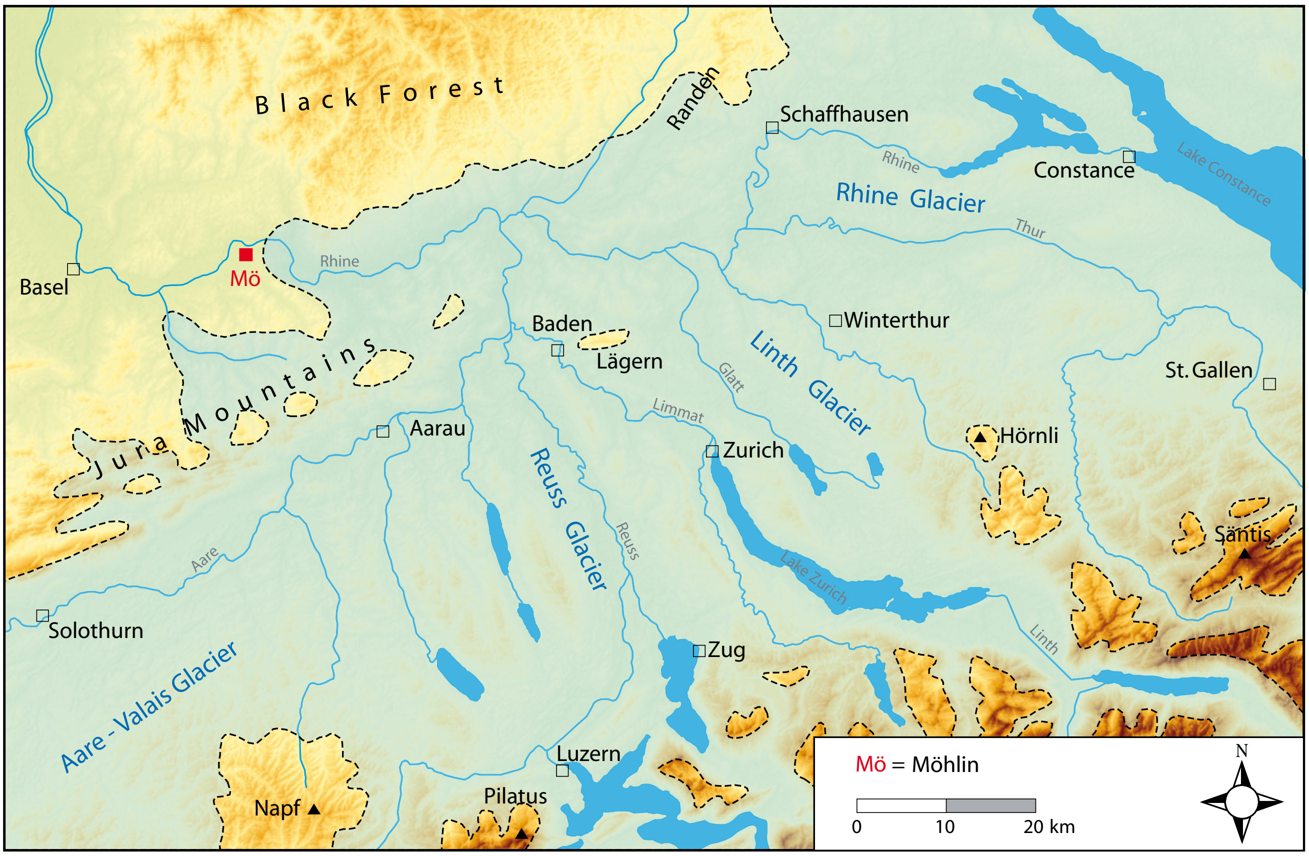

Fig. 20: Estimated maximal ice extent during the Möhlin glaciation (re-drawn after KELLER & KRAYSS 2010; elevation data from JARVIS et al. 2008).

Abb. 20: Geschätzte maximale Eisausdehnung während der Möhlin-Eiszeit (umgezeichnet nach KELLER & KRAYSS 2010; Höhendaten von JARVIS et al. 2008).

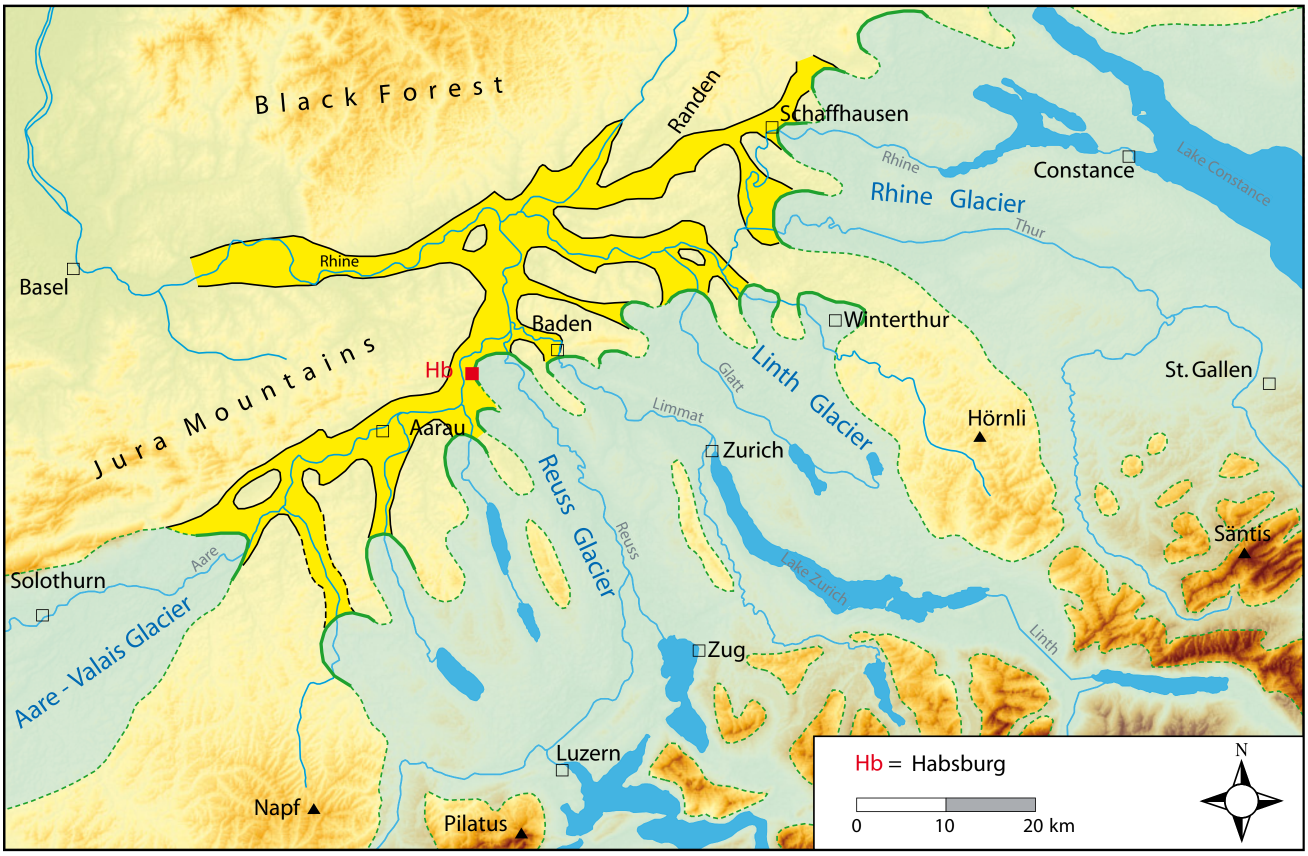

Fig. 21: Estimated maximal ice extent during the Habsburg glaciation (re-drawn after KELLER & KRAYSS 2010; elevation data from JARVIS et al. 2008).

Abb. 21: Geschätzte maximale Eisausdehnung während der Habsburg-Eiszeit (umgezeichnet nach KELLER & KRAYSS 2010; Höhendaten von JARVIS et al. 2008).

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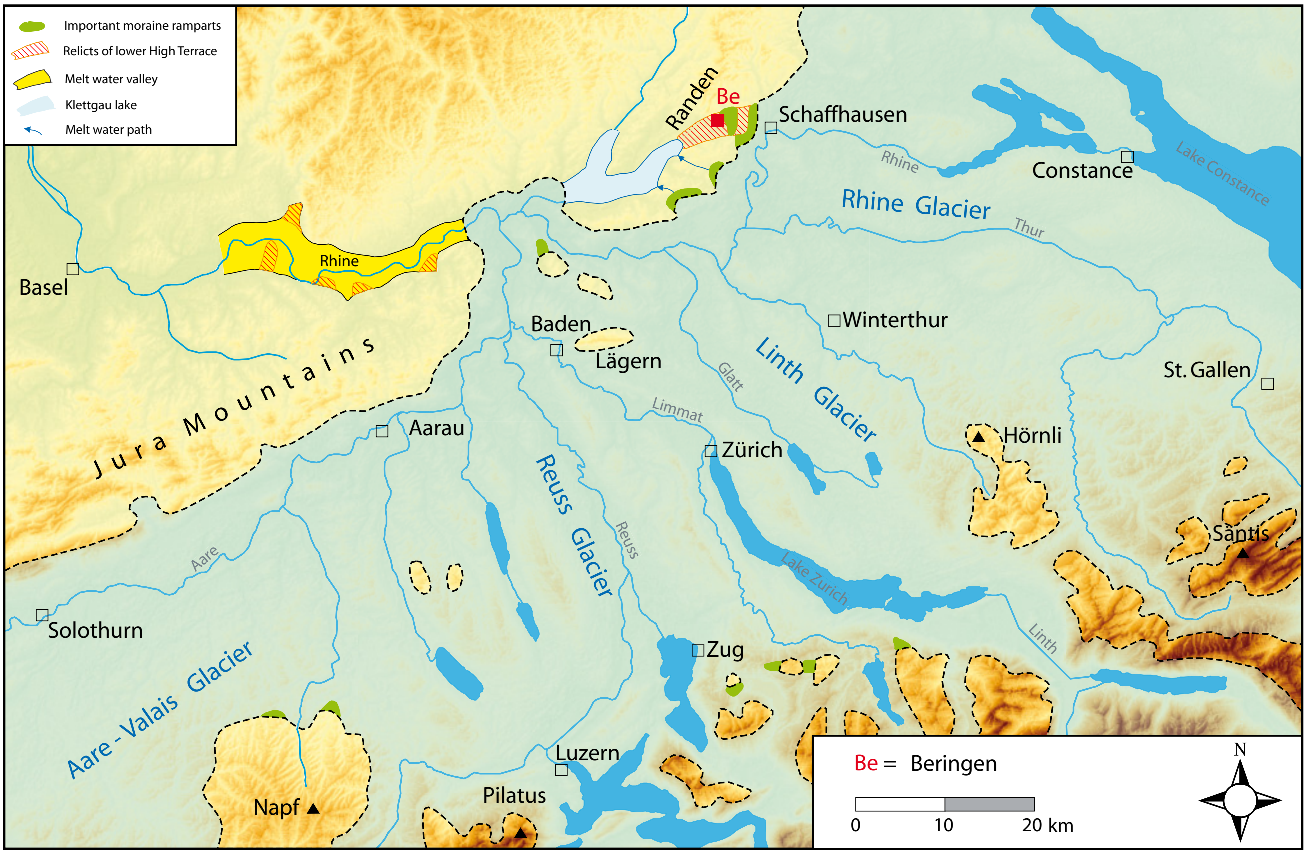

Fig. 22: Estimated maximal ice extent during the Beringen glaciation (re-drawn after KELLER & KRAYSS 2010; elevation data from JARVIS et al. 2008).

Abb. 22: Geschätzte maximale Eisausdehnung während der Beringen-Eiszeit (umgezeichnet nach KELLER & KRAYSS 2010; Höhendaten von JARVIS et al. 2008).

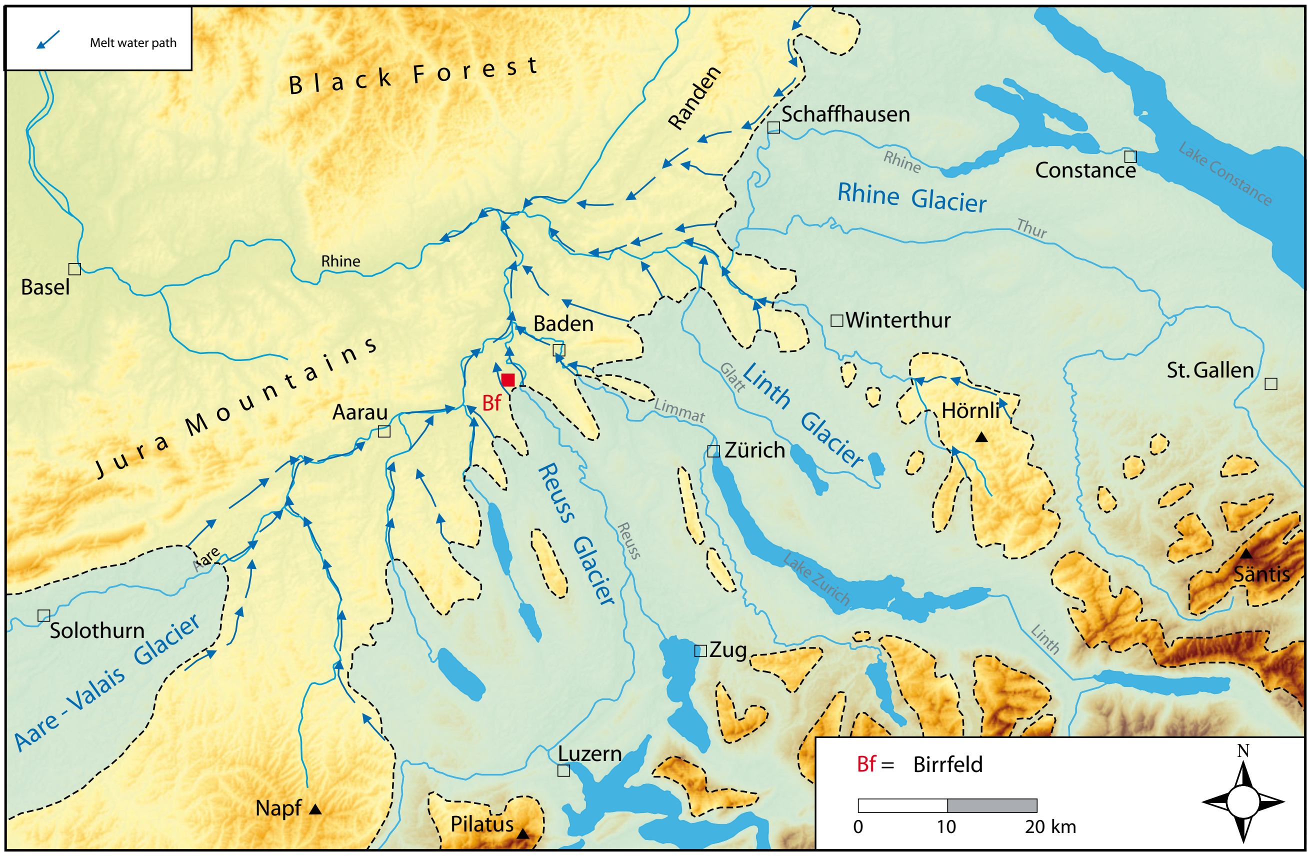

Fig. 23: Observed maximal ice extent during the Birrfeld glaciation (re-drawn after KELLER & KRAYSS 2010; elevation data from JARVIS et al. 2008).

Abb. 23: Beobachtete maximale Eisausdehnung während der Birrfeld-Eiszeit (umgezeichnet nach KELLER & KRAYSS 2010; Höhendaten von JARVIS et al. 2008).

4 Glaciation history

4.1 Early Pleistocene ('Deckenschotter glaciations')

During the Pliocene/Pleistocene transition, the landscape of the northern foreland of the Swiss Alps most likely had a much less pronounced relief than today. This is deduced from the fact that the channels, in which 'Höhere Deckenschotter' were deposited, have a broad and flat cross-section. Proof for glaciations reaching the Swiss lowlands during the Early Quaternary is limited and relies mainly on the presence of thin till layers within the coarse gravel deposits. It is assumed that glaciers at that time were more of a piedmont type than being valley glaciers. However, there is local evidence for glacial basins, for example, at Uetliberg near Zurich (Graf & Müller 1999). For 'Höhere Deckenschotter', two ice advances into the lowlands are documented by the presence of glacial deposits, one reaching north of the Lägern, the other even reaching the lower Aare Valley (i.e. the region between the confluence of Aare/Reuss/Limmat and the confluence of Aare/Rhine).

Evidence for the presence of glaciers in the lowlands for the time of 'Tiefere Deckenschotter' is limited to Iberig and Schiener Berg (near Lake Constance). The till-complexes found there are much thicker than those found within 'Höhere Deckenschotter', and two ice advances are well documented by the presence of glacial sediments, at least reaching Iberig in the lower Aare Valley. Interestingly, at that time the ice advance in the Reuss Valley was apparently more pronounced than in the Rhine Valley, compared to the Last Glaciation.

An important observation is that both 'Deckenschotter' units comprise several subunits with both glacial and interglacial character, and thus probably represent at least some 100 ka. The lower bedrock level of 'Tiefere Deckenschotter' implies a period of substantial incision between both units (Fig. 18). The mechanism behind these periods of pronounced erosion could be either uplift of the Alps, or in the Jura and Black Forest, or subsidence in the Upper Rhine Graben. Both scenarios would have led to a higher gradient of the drainage system with regard to the base level in the southern part of the Upper Rhine Graben, causing incision in the upper reaches to the river systems.

Most pronounced is the incision after deposition of 'Tiefere Deckenschotter' (Fig. 18). Besides tectonic processes, this may have been caused by the redirection of the Alpine Rhine that was tributary to the River Danube during most of the Early Pleistocene (cf. Preusser 2008; Keller 2009). The connection of the Alpine Rhine, flowing at a level of about 700 m a.s.l., to the base level in the southern part of the Upper Rhine Graben, being at ca. 250 m a.s.l., must have caused substantial fluvial incision along the Hochrhein and its tributaries (systems of the Rivers Aare, Reuss, and Limmat). This complex change of drainage and relief is currently not directly dated, but we refer to it as Middle Pleistocene Reorganisation (MPR).

4.2 Middle-Late Pleistocene of central northern Switzerland

After the period of pronounced fluvial incision following the 'Deckenschotter' period (MPR), alpine glaciers advanced to their most extensive position during the Quaternary (Fig. 19). The Möhlin Glaciation reached the southern slopes of the Black Forest (Fig. 20). Sediment attributed to this glacial advance is rare, but this glaciation probably carved the first overdeepened glacial basins in the Swiss lowlands and widened the pre-existing valleys. The following glaciation, Habsburg (Fig. 21), was of a much more limited extent compared to Möhlin and only reached to the northern margins of the deep basins in the northern Swiss lowlands, with one front of the Reuss Glacier situated near the type location of Habsburg (Fig. 21). From the terminal position of this glacial advance substantial masses of sediment where deposited along the drainage paths, i.e. the Rivers Aare and Rhine, and form part of the High Terrace deposits in these valleys. In the internal parts of the glacial basins, a continuation of glacial erosion is documented by glacial deposits (till), followed by lacustrine sedimentation. The transition to the next interglacial is often characterised by delta deposits and, in particular, peat.

Till deposits in the upper and middle parts of Glatt Valley and in the Thur Valley show intercalating lake sediments and gravel ('Aathal-Schotter') (Kempf 1986; Wyssling 2008; Müller 1996), which point towards a glacial advance that probably reached the Linth and Lake Constance basins after the Habsburg Glaciation but prior to the main advance of the Beringen Glaciation. While Graf (2009a) refers to this advance as an independent glaciation (Hagenholz), Keller & Krayss (2010) interpret it as an early advance of the Beringen Glaciation (Fig. 19).

The main advance of the Beringen Glaciation is documented by till found all over the study area in northern Switzerland. This advance has overrun the previously deposited High Terraces and crossed the River Rhine between the cities of Schaffhausen and Waldshut (Fig. 22). At the same time, the Lake Constance-Rhine Glacier advanced into the upper parts of Klettgau leaving large amounts of pro-glacial melt water deposits. Concurrently, the Aare-Reuss-Linth Glacier blocked the lower part of Klettgau, leaving an ice-dammed lake. Outwash deposits blocked the Neuhauserwald and Engi channels, forcing the River Rhine to a southerly direction (Fig. 9). The main advance of the Beringen Glaciation left gravel on top of older lake deposits and this glacial advance likely caused the formation of some new glacial basins.

The Birrfeld Glaciation (Late Pleistocene) left a variety of geomorphological features, which are well preserved due to its relatively young age. Evidence for one or even two glacial advances during the early part of this glaciation has been discussed on several occasions (Schlüchter et al. 1987; Keller & Krayss 1998; Preusser et al. 2003; Preusser 2004; Ivy-Ochs et al. 2008). According to present dating evidence, these glacial advances occurred during MIS 5d and/or MIS 4, and represent independent phases of ice build-up and decay (cf. Ivy-Ochs et al. 2008). Following Keller & Krayss (1998), the MIS 4 advance reached Untersee and was only some 10 km less extensive than the Last Glaciation of the Swiss lowlands.

The period between 55–30 ka was characterised by relative moderate climatic conditions, best documented by the Gossau Interstadial Complex (Schlüchter et al. 1987; Preusser et al. 2003) and to some extend at Niederweningen (Furrer et al. 2007, and references therein). The main

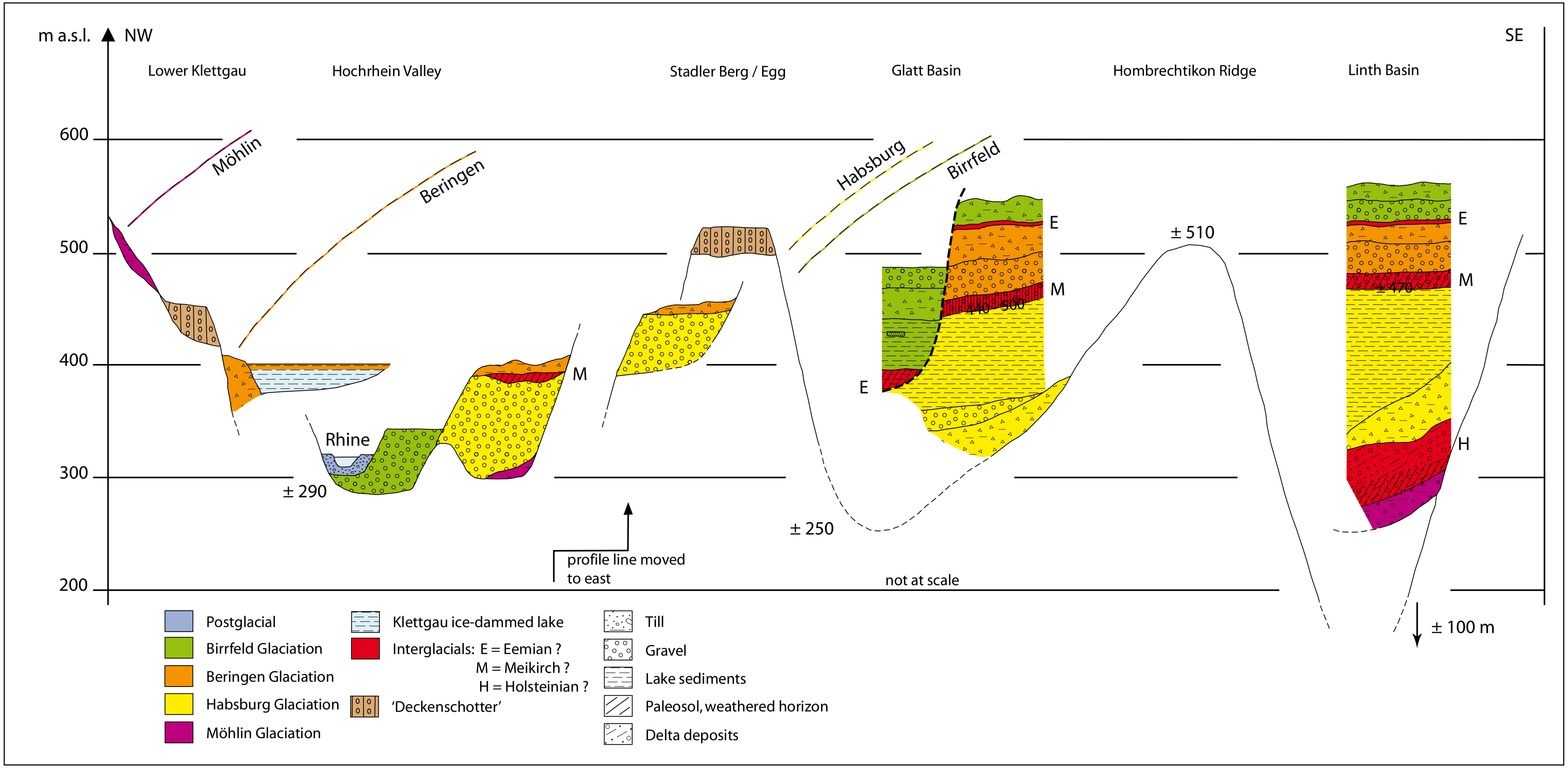

Fig. 24: Generalised cross section from the Hochrhein to the Linth Basin (re-drawn after Keller & Krayss *2010).*

Abb. 24: Generalisierter Profilschnitt vom Hochrhein ins Linth Becken (umgezeichnet nach Keller & Krayss *2010).*

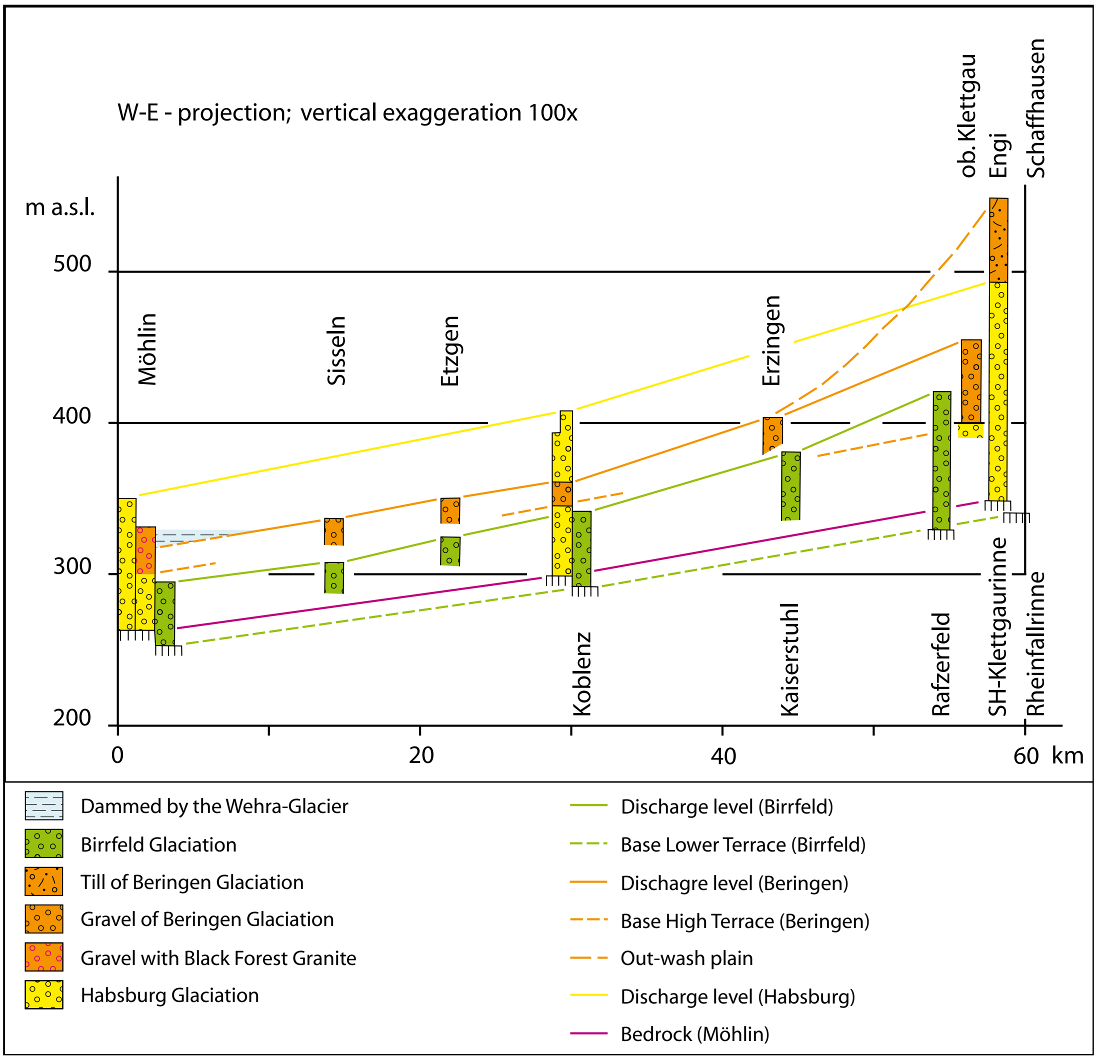

Fig. 25: Evolution of relief along the Hochrhein (re-drawn after Keller & Krayss 2010).

Abb. 25: Reliefentwicklung entlang des Hochrheins (umgezeichnet nach Keller & Krayss 2010).

advance of the Birrfeld Glaciation (Fig. 23) occurred after ca. 30 ka ago and reached its maximum position probably about 24–22 ka. By ca. 17.5 ka at the latest, the ice had disappeared from the Swiss lowlands (cf. Amman et al. 1994; Preusser 2004; Keller & Krayss 2005b).

The generalised cross-section from the Linth Basin via the Glatt Valley towards the Hochrhein Valley (Fig. 24) demonstrates the impact of Quaternary glaciations on the geomorphology and summarises its imprint in the sedimentological record. In the deep basins, sedimentary successions reflect the changing depositional environments during past glacial and interglacial times. The latter are mainly represented by palaeosols and peat deposits. Incised valleys and terraces mainly made up by gravel deposits reflect ice-marginal and proglacial settings.

The evolution of the relief during the last major glaciations is shown with a west-east projection along the Hochrhein Valley between Möhlin and Schaffhausen (Fig. 25). The deep channel incised into bedrock indicates the end of erosional processes that dominated since the end of the 'Deckenschotter' period and continued until the Möhlin Glaciation. Above the base of this channel, gravel of the Habsburg Glaciation accumulated with a thickness of 70–140 m, up to the surface of the High Terrace. The elevation of the base of gravel deposition during the Beringen Glaciation is poorly known. Better constrained is the flow line of the maximum advance during this glaciation, from the proximal proglacial setting near Schaffhausen to Möhlin. During the following interglacial erosion down to the bedrock surface in partly newly incised channels was even deeper, forming the base of Low Terrace gravel with a maximal flow line originating from Rafzerfeld.

4.3 Middle-Late Pleistocene of the Aare Valley

Due to its geographical position, evidence from the middle part of the Aare Valley cannot directly be linked to the findings of central northern Switzerland summarised in the previous paragraphs. Nevertheless, this region is of eminent importance as most of the geochronological and palynostratigraphical information has been collected from outcrops and drill holes in this area. The oldest deposits of the region are the basal glacial sediments at Thalgut, situated below lake deposits bearing a flora with *Fagus* and *Pterocarya*. This interglacial with *Pterocarya* is interpreted to represent an equivalent of the Praclaux Interglacial in the Massif Central,

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France, and of the Holsteinian as defined in northern Germany (cf. Beaulieu et al. 2001). The age of the Holsteinian is generally accepted as MIS 11 (ca. 420 ka) and this age is apparently verified by $^{40}Ar/^{39}Ar$ dating of tephra some metres above the Praclaux Interglacial deposits (Roger et al. 1999). In contrast, Geyh & Müller (2005) report U/Th ages of about 325 ka for peat layers with a Holsteinian pollen signature from northern Germany, rather implying a correlation with MIS 9. Above the interglacial containing *Pterocarya* follows another glaciation that at least reached the Thalgut site. The Meikirch site implies the presence of a glacier at this site during MIS 8 and a complex pattern of environmental change during MIS 7, with three pronounced warm periods. The dating results from Landiswil and erratic boulders from the Jura Mountains imply an extensive glaciation of the Swiss lowland during MIS 6. First evidence from Thalgut (Preusser & Schlüchter 2004) and Finsterhennen (Preusser et al. 2007) points towards one or even two ice advances after the Last Interglacial but prior to the Last Glaciation. However, this needs to be verified by further data.

4.4 Correlations between central northern Switzerland and the Aare Valley

Of eminent importance for correlations and establishing a chronology is the occurrence of interglacial deposits in the Aare Valley that are present but not well investigated in the central and eastern parts of Switzerland. The oldest glaciation documented in the Aare Valley is older than Holsteinian, but we can only speculate that it is an equivalent of the Möhlin Glaciation. A glaciation younger than Holsteinian (minimum age 320 ka) but older than Meikirch is documented in the Aare Valley (Preusser et al. 2005) and could well be an equivalent of the Habsburg Glaciation. Considering the dating evidence from Landiswil, the Jura Mountains, and the Schaffhausen area, the extensive Beringen glaciation is likely to represent MIS 6 (ca. 180–130 ka). In northern Switzerland this advance reached beyond the River Rhine and was substantially more extensive than the last advance of the Birrfeld Glaciation.

The limited number of reliable geochronological and palynostratigraphical tie-points leaves some uncertainty with the chronological framework presented in Figure 19. However, the general scheme appears rather consistent with at least four, but probably up to seven glacial advances reaching the Swiss lowlands during the younger Middle and Late Pleistocene (< 500 ka).

5 Conclusions

Evidence from the northern foreland of the Swiss Alps indicates at least eight, but probably more lowland glaciations during the Quaternary. At least two glacial advances reached northern Switzerland during the time of the 'Höhere Deckenschotter' (older Early Pleistocene) and a minimum of two further advances occurred during the phase of 'Tiefere Deckenschotter' (younger Early Pleistocene to older Middle Pleistocene?). Both periods were followed by pronounced periods of fluvial incision, possible caused by tectonic movements and probably enhanced by fluvial dynamics during the second phase (re-direction of the Alpine Rhine, MPR). The most extensive glaciation of the Quaternary is represented by the Möhlin Glaciation and is assumed to be older than Holsteinian. It is followed by the Habsburg Glaciation that was presumably of a similar size to the Last Glaciation of the Swiss lowland. The glacial extent during the subsequent Beringen Glaciation was again rather extensive. Luminescence and cosmogenic nuclide dating imply that this period is likely equivalent to MIS 6 (180–130 ka). The last glacial cycle, Birrfeld, may comprise two, or even three, periods of individual ice build-up and decay, separated by phases with relatively mild temperatures. The last glacier advance reached the lowland just after 30 ka ago, reached its maximum ca. 24–22 ka, and disappeared from the lowlands not later than 17.5 ka.

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References

Agassiz, L. (1837): Discours prononcé à l'ouverture des séances de la Société Helvétique des Sciences Naturelles. – Actes de la Société Helvétique des Sciences Naturelles, Neuchâtel.

Amman, B., Lotter, A., Eicher, U., Gaillard, M.-J., Wohlfarth, B., Haeberli, W., Lister, G., Maisch, M., Niessen, F. & Schlüchter, Ch. (1994): The Würmian Late-glacial in lowland Switzerland. – Journal of Quaternary Science, 9: 119–125.

Beaulieu, J.-L. de, Andrieu-Ponel, V., Reille, M., Grüger, E., Tzedakis, C. & Svobodova, H. (2001): An attempt at correlation between the Velay pollen sequence and the Middle Pleistocene stratigraphy from central Europe. – Quaternary Science Reviews, 20: 1593–1602.

Bini, A., Buoncristiani, J.-F., Couterrand, S., Ellwanger, D., Felber, M., Florineth, D., Graf, H.R., Keller, O., Kelly, M., Schlüchter, C., & Schoeneich, P. (2009): Die Schweiz während des letzteiszeitlichen Maximums (LGM). – Map 1 : 500 000, swisstopo.

Bolliger, T., Feijfar, O., Graf, H.R. & Kälin, D.W. (1996): Vorläufige Mitteilung über Funde von pliozänen Kleinsäugern ais den Höheren Deckenschottern des Irchels (Kt. Zürich). – Eclogae geologicae Helvetiae, 89: 1043–1048.

Brockmann-Jerosch, H. (1910): Die fossilen Pflanzenreste des glazialen Deltas bei Kaltbrunn (bei Uznach, Kanton St. Gallen) und deren Bedeutung für die Auffassung des Wesens der Eiszeit. – Jahrbuch St. Gallische Naturwissenschaftliche Gesellschaft. Habilschrift Universität Zürich.

Charpentier, J. de (1841): Essai sur les glaciers et sur le terrain erratique di Bassin du Rhône.

Dehnert, A., Preusser, F., Kramers, J.D., Akçar, N., Kubik, P.W., Reber, R. & Schlüchter, C. (2010): A multi-dating approach applied to proglacial sediments attributed to the Most Extensive Glaciation of the Swiss Alps. – Boreas, 39: 620–632.

Eberl, B. (1930): Die Eiszeitenfolge im nördlichen Alpenvorland. – Benno Filser Verlag, Augsburg.

Fiebig, M. & Preusser, F. (2003): Das Alter fluvialer Ablagerungen aus der Region Ingolstadt (Bayern) und ihre Bedeutung für die Eiszeitenchronologie des Alpenvorlandes. – Zeitschrift für Geomorphologie – Neue Folge, 47: 449–467.

Florineth, D. (1998): Surface geometry of the Last Glacial Maximum (LGM) in the southeastern Swiss Alps (Graubünden) and its paleoclimatological significance. – Eiszeitalter und Gegenwart, 48: 23–37.

Florineth, D. & Schlüchter, C. (1998): Reconstructing the Last Glacial Maximum (LGM) ice surface geometry and lowlines in the Central Swiss Alps. – Eclogae geologicae Helvetiae, 91: 391–407.

Florineth, D. & Schlüchter, C. (2000): Alpine evidence for atmospheric circulation patterns in Europe during the Last Glacial Maximum. – Quaternary Research, 54: 295–308.

Furrer, H., Graf, H.R. & Mäder, A. (2007): The mammoth site of Niederweningen, Switzerland. – Quaternary International, 164–165: 85–97.

Gerber, E. (1941): Über Höhenschotter zwischen Emmental und Aaretal. – Eclogae geologicae Helvetiae, 34: 1–16.

Gerber, E. (1950): Blatt 22: Fraubrunnen – Wynigen – Hindelbank – Burgdorf (SA 142–145), mit nördlichem Teil von Blatt 321 Bigenthal. Erläuterungen zum Geologischer Atlas der Schweiz 1 : 25 000. – Bundesamt für Landestopographie, Bern.

Geyh, M.A. & Müller, H. (2005): Numerical 230Th/U dating and a palynological review of the Holsteinian/Hoxonian Interglacial. – Quaternary Science Reviews, 24: 1861–1872.

Graf, A.A., Strasky, S., Ivy-Ochs, S., Akçar, N., Kubik, P. W., Burkhard, M. & Schlüchter, C. (2007): First results of cosmogenic dated pre-Last Glaciation erratics from the Montoz area, Jura Mountains, Switzerland. – Quaternary International, 164–165: 43–52.

Graf, H.R. (1993): Die Deckenschotter der Zentralen Nordschweiz. – Diss. ETH Zürich Nr. 10205, 151 S.

Graf, H.R. (2009a): Stratigraphie von Mittel- und Spätpleistozän in der Nordschweiz. – Beiträge zur Geologischen Karte der Schweiz, 168, Bundesamt für Landestopografie swisstopo, Wabern.

Graf, H.R. (2009b): Stratigrafie und Morphogenese von frühpleistozänen Ablagerungen zwischen Bodensee und Klettgau. E&G – Quaternary Science Journal 58, 12–54.

Graf, H.R. & Müller, B. (1999): Das Quartär: Die Epoche der Eiszeiten. In: Bolliger, Th. (Ed.) Geologie des Kantons Zürich, 71–95, Ott Verlag, Thun.

Gruner, U. (2001): Blatt 104: Worb (LK 1167). Erläuterungen zum Geologischer Atlas der Schweiz 1 : 25 000. – Bundesamt für Landestopographie, Bern.

Ivy-Ochs, S., Schäfer, J., Kubik, P.W., Synal, H.-A. & Schlüchter, C. (2004): Timing of deglaciation on the northern alpine foreland (Switzerland). – Eclogae geologicae Helvetiae, 97: 47–55.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Kubik, P.W., Maisch, M. & Schlüchter, C. (2008): Chronology of the last glacial cycle in the European Alps. – Journal of Quaternary Science, 23: 559–573.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Chritl, M., Kubik, P.W. & Schlüchter, C. (2009): Latest Pleistocene and Holocene glacier variations in the European Alps. Quaternary Science Reviews, 28: 2137–2149.

Haldimann, P.A. (1978): Quartärgeologische Entwicklung des mittleren Glattals (Kt. Zürich). – Eclogae geologicae Helvetiae, 71: 347–355.

Jarvis A., Reuter, H.I., Nelson, A., Guevara, E. (2008): Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT). (available from http://srtm.csi.cgiar.org)

Jeannet, A. (1923): Les charbons feuilletés de la vallée de la Linth entre les lacs de Zurich et de Walenstadt. In: Baumberger, E., Gerber, E., Jeannet, A. & Weber J. (Eds.): Die diluvialen Schieferkohlen der Schweiz. – Beiträge Geologie der Schweiz, geotechnische Serie VIII, 106–370.

Keller, O. (1994): Entstehung und Entwicklung des Bodensees – ein geologischer Lebenslauf. – In: Maurer, H. (Ed.): Umweltwandel am Bodensee. – Fachverlag UVK, 33–92; St. Gallen, Konstanz.

Keller, O. (2005): Letzte Eiszeit und Landschaftsformung am Hochrhein und am Alpenrhein. – In: Der Rhein – Lebensader einer Region. Neujahrsblatt der Naturforschenden Gesellschaft in Zürich, 54–74.

Keller, O. (2009): Als der Alpenrhein sich von der Donau zum Oberrhein wandte. – Schriften des Vereins für Geschichte des Bodensees und seiner Umgebung, 127: 193–208.

Keller, O. & Krayss, E. (1998): Datenlage und Modell einer Rhein-Linth-Vorlandvergletscherung zwischen Eem-Interglazial und Hochwürm. – GeoArchaeoRhein, 2: 121–138.

Keller, O. & Krayss, E. (1999): Quartär und Landschaftsgeschichte. – Erläuterungen zur Geologischen Übersichtskarte des Kantons Thurgau. – Mitteilungen der Thurgauischen Naturforschenden Gesellschaft, 55: 39–67.

Keller, O. & Krayss, E. (2005a): Der Rhein-Linth-Gletscher im letzten Hochglazial. 1. Teil: Einleitung; Aufbau und Abschmelzen des Rhein-Linth-Gletschers im Oberen Würm. – Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, 150: 19–32.

Keller, O. & Krayss, E. (2005b): Der Rhein-Linth-Gletscher im letzten Hochglazial. 2. Teil: Datierung und Modelle der Rhein-Linth-Vergletscherung. Klima-Rekonstruktionen. – Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, 150: 69–85.

Keller, O. & Krayss, E. (2010): Mittel- und spätpleistozäne Stratigraphie und Morphogenese in Schlüsselregionen der Nordschweiz. – E&G Quaternary Science Journal, 59: 88–119.

Kelly, M.A., Buoncristiani, J.-F. & Schlüchter, C. (2004): A reconstruction of the last glacial maximum (LGM) ice-surface geometry in the western Swiss Alps and contiguous Alpine regions in Italy and France. – Eclogae geologicae Helvetiae, 97: 57–75.

Kempf, T. (1986): In: Direktion der öffentlichen Bauten des Kantons Zürich: Die Grundwasservorkommen im Kanton Zürich, Erläuterungen zur Grundwasserkarte des Kantons Zürich 1 : 25 000, 211 S. – Beiträge zur Geologie der Schweiz, Geotechnische Serie 69; ETH 8092 Zürich.

Kock, S., Huggenberger, P., Preusser, F., Rentzel, P. & Wetzel, A. (2009): Formation and evolution of the Lower Terrace of the Rhine River in the area of Basel. – Swiss Journal of Geosciences, 102: 307–321.

Longo, W. (1978): Geologie des Hagenholztunnels bei Kloten. – Eclogae geologicae Helvetiae, 71: 175–182.

Mailänder, R. & Veit, H. (2001): Periglacial cover beds on the Swiss Plateau: indicators of soil, climate and landscape evolution during the Late Quaternary. – Catena, 45: 251–272.

Müller, E.R. (1996): Die Ittinger Schotter und ihr morphogenetisches Umfeld. – Eclogae geologicae Helvetiae, 89: 1077–1093.

Penck, A. & Brückner, E. (1901/09): Die Alpen im Eiszeitalter. – Tauchnitz, Leipzig.

Preusser, F. (1999): Luminescence dating of fluvial sediments and overbank deposits from Gossau, Switzerland: fine grain dating. – Quaternary Science Reviews 18: 217–222.

Preusser, F. (2004): Towards a chronology of the Upper Pleistocene in the northern Alpine Foreland. – Boreas, 33: 195–210.

Preusser, F. (2008): Characterisation and evolution of the River Rhine system. – Netherlands Journal of Geosciences, 87: 7–19.

Preusser, F., Geyh., M.A. & Schlüchter, C. (2003): Timing of Late Pleistocene climate change in lowland Switzerland. – Quaternary Science Reviews, 22: 1435–1445.

Preusser, F. & Graf, H.R. (2002): Erste Ergebnisse von Lumineszenzdatierungen eiszeitlicher Ablagerungen der Nordschweiz. – Jahrbuch und Mitteilungen des Oberrheinischen Geologischen Vereins, 107: 419–438.

Preusser, F. & Schlüchter, C. (2004): Dates from an important early Late Pleistocene ice advance in the Aare Valley, Switzerland. – Eclogae geologicae Helvetiae, 97: 245–253.

Preusser, F., Drescher-Schneider, R., Fiebig, M. & Schlüchter, C. (2005): Re-interpretation of the Meikirch pollen record, Swiss Alpine Foreland, and implications for Middle Pleistocene chronostratigraphy. – Journal of Quaternary Science, 20: 607–620.

Preusser, F., Blei, A., Graf, H.R. & Schlüchter, C. (2007): Luminescence dating of proglacial sediments from Switzerland. – Boreas, 36: 130–142.

Preusser, F., Reitner, J. & Schlüchter, C. (2010). Distribution, geometry, age and origin of overdeepened valleys and basins in the Alps and their foreland. Swiss Journal of Geosciences, 103: 407–427.

Roger, S., Féraud, G., de Beaulieu, J.-L., Thouveny, N., Coulon, Ch., Choucemé, J.J., Andrieu, V. & Williams, T. (1999): $^{40}Ar/^{39}Ar$ dating on tephra of the Velay maars (France): implications for the Late Pleistocene proxy-climatic record. – Earth and Planetary Science Letters, 170: 287–299.

Schaefer, I. (1957) : Erläuterungen zur Geologischen Karte von Augsburg und Umgebung 1 : 50 000. – Bayrisches Geologisches Landesamt München.

Schindler, C. (2004): Zum Quartär des Linthgebietes zwischen Luchsingen, dem Walensee und dem Zürcher Obersee. – Beiträge zur Geologischen Karte der Schweiz, 159 S. – Bundesamt für Landestopografie swisstopo; Wabern.

Schlüchter, C. (1987a): Lokale Vergletscherung im westlichen Ausläufer des Napfberglandes. – Eiszeitalter und Gegenwart, 37: 41–45.

Schlüchter, C. (1987b): Talgenese im Quartär – eine Standortbestimmung. Geographica Helvetica, 2: 109–115.

Schlüchter, C. (1988): A non-classical summary of the Quaternary stratigraphy in the northern alpine Foreland of Switzerland. – Bulletin de la Société neuchâteloise de géographie, 32: 143–157.

Schlüchter, C. (1989a): The most complete Quaternary record of the Swiss Alpine Foreland. – Palaeogeography, Palaeoclimatology, Palaeoecology, 72: 141–146.

Schlüchter, C. (1989b): Thalgut: Ein umfassendes eiszeitstratigraphisches Referenzprofil im nördlichen Alpenvorland. – Eclogae geologicae Helvetiae, 82: 277–284.

Schlüchter, C., Maisch, M., Suter, J., Fitze, P., Keller, W.A., Burga, C.A. & Wynistorf, E. (1987): Das Schieferkohlenprofil von Gossau (Kanton Zürich) und seine stratigraphische Stellung innerhalb der letzten Eiszeit. – Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, 132: 135–174.

Schlüchter, C. & Kelly, M. (2000): Das Eiszeitalter in der Schweiz. – Stiftung Landschaft und Kies, Uttigen.

Schreiner, A. & Ebel, R. (1981): Quartärgeologische Untersuchungen in der Umgebung von Interglazialvorkommen im östlichen Rheingletschergebiet (Baden-Württemberg). – Geologisches Jahrbuch, A59: 3–64.

Venetz, I. (1833): Mémoire sur les variation de la temperature dans les Alps de la Suisse. – Denkschriften der allgemeinen Schweizerischen Gesellschaft für die gesamte Natur, 1.

Venetz, I. (1861): Mémoire sur l`extension des ancient glaciers, renfermant quelques explications sur leurs effects remarquables. – Neue Denkschrift der allgemeinen Schweizerischen Gesellschaft für die gesamte Natur, 18.

Welten, M. (1982): Pollenanalytische Untersuchungen im Jüngeren Quartär des nördlichen Alpenvorlandes der Schweiz. – Beiträge zur Geologischen Karte der Schweiz N. F. 156, 174 pp.; Bern.

Welten, M. (1988): Neue pollenanalytische Ergebnisse über das Jüngere Quartär des nördlichen Alpenvorlandes der Schweiz (Mittel- und Jungpleistozän). – Beiträge zur Geologischen Karte der Schweiz N.F. 162, 40 pp.; Bern.

Wyssling, L. & Wyssling, G. (1978): Interglaziale Seeablagerungen in einer Bohrung bei Uster (Kt. Zürich). – Eclogae geologicae Helvetiae, 71: 357–375.

Wyssling, G. (2008): Blatt 1092 Uster. Geologischer Atlas der Schweiz, Erläuterungen 128. – Bundesamt für Landestopografie swisstopo; Wabern.

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The Quaternary of the southwest German Alpine Foreland (Bodensee-Oberschwaben, Baden-Württemberg, Southwest Germany)

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Abstract: The Quaternary of the 'Bodensee' region comprises Early Pleistocene fluvial gravels ('Deckenschotter') and Middle and Late Pleistocene glacial and meltwater deposits of the Rhineglacier. They reflect the transformation of the alpine margin from a foothill ramp to the overdeepened amphitheatre (today's topography). The 'Deckenschotter' reflect not only fluvial incision but also, according to major differences in petrographical composition, the evolution of their alpine source area (alpine Rhine Valley). The eldest glacial till is in contact with the 'Mindel-Deckenschotter', displaying no evidence of major overdeepening in this early time slice. Most glacial and meltwater deposits are attributed to three major foreland glaciations of the Rhineglacier forming three generations of overdeepened basins. The eldest basins are directed northward to the Donau, those of the last glaciation go west towards the Rhine. This re-orientation improves the resolution of glacial sediments and landforms. The glacial deposits are traditionally described as chronostratigraphical system based upon glacial versus interglacial units. In this paper, an updated version of this chronostratigraphy is presented, supplemented by a lithostratigraphical system that primarily focusses on sediment bodies. Finally, short definitions of major lithostratigraphical units are outlined that are used by the Geological Survey of the German State of Baden-Württemberg.

[Das Quartär des südwestdeutschen Alpenvorlandes (Bodensee-Oberschwaben, Baden-Württemberg, Südwestdeutschland)]

Kurzfassung: Das Quartär der Bodensee-Region besteht aus Schottern frühpleistozäner alpiner Flusssysteme (Deckenschotter) sowie aus glazialen und Schmelzwasser-Ablagerungen der mittel- und spätpleistozänen Eiszeiten. Sie belegen den landschaftlichen Wandel von einer Art Rampe aus Vorbergen hin zur heutigen Topographie mit ineinander greifenden, übertieften Becken, sodass sich eine Art Amphitheater ergibt. Die Deckenschotter als älteste Ablagerungen dokumentieren einerseits die Eintiefung der alpinen Flüsse in diversen Terrassenstufen im Sedimentationsgebiet, andererseits durch deutliche Unterschiede im Geröllspektrum die Vergrößerung des Liefergebiets des sich entwickelnden alpinen Rheins. Der älteste Till kommt vor in Kontakt mit Mindel-Deckenschottern, es gibt jedoch keine Hinweise auf eine glaziale Übertiefung in dieser Zeit. Die meisten glazialen und Schmelzwasser-Ablagerungen werden drei großen Vergletscherungen des Rheingletschers zugeordnet. Diese Vorlandvergletscherungen sind mit drei Generationen glazialer Becken verknüpft. Die ältesten Becken sind zur Donau orientiert, die aus der letzten Vereisung entwässern zum Rhein. Diese Reorientierung bewirkte die hervorragende räumliche Auflösung der Sedimente und Formen. Traditionell wurden die Sedimente in einem chronostratigraphischen System aus glazialen und interglazialen Stufen beschrieben. Unsere Ziele in dieser Arbeit sind, eine Aktualisierung des chronostratigraphischen Systems vorzustellen, das neue, beim geologischen Dienst von Baden-Württemberg angewandte, lithostratigraphische Schema zu erklären und die wichtigsten neuen Einheiten kurz zu beschreiben.

Keywords: *Pleistocene, Rhineglacier, chronostratigraphy, lithostratigraphy, Deckenschotter, glacial deposits, overdeepening*

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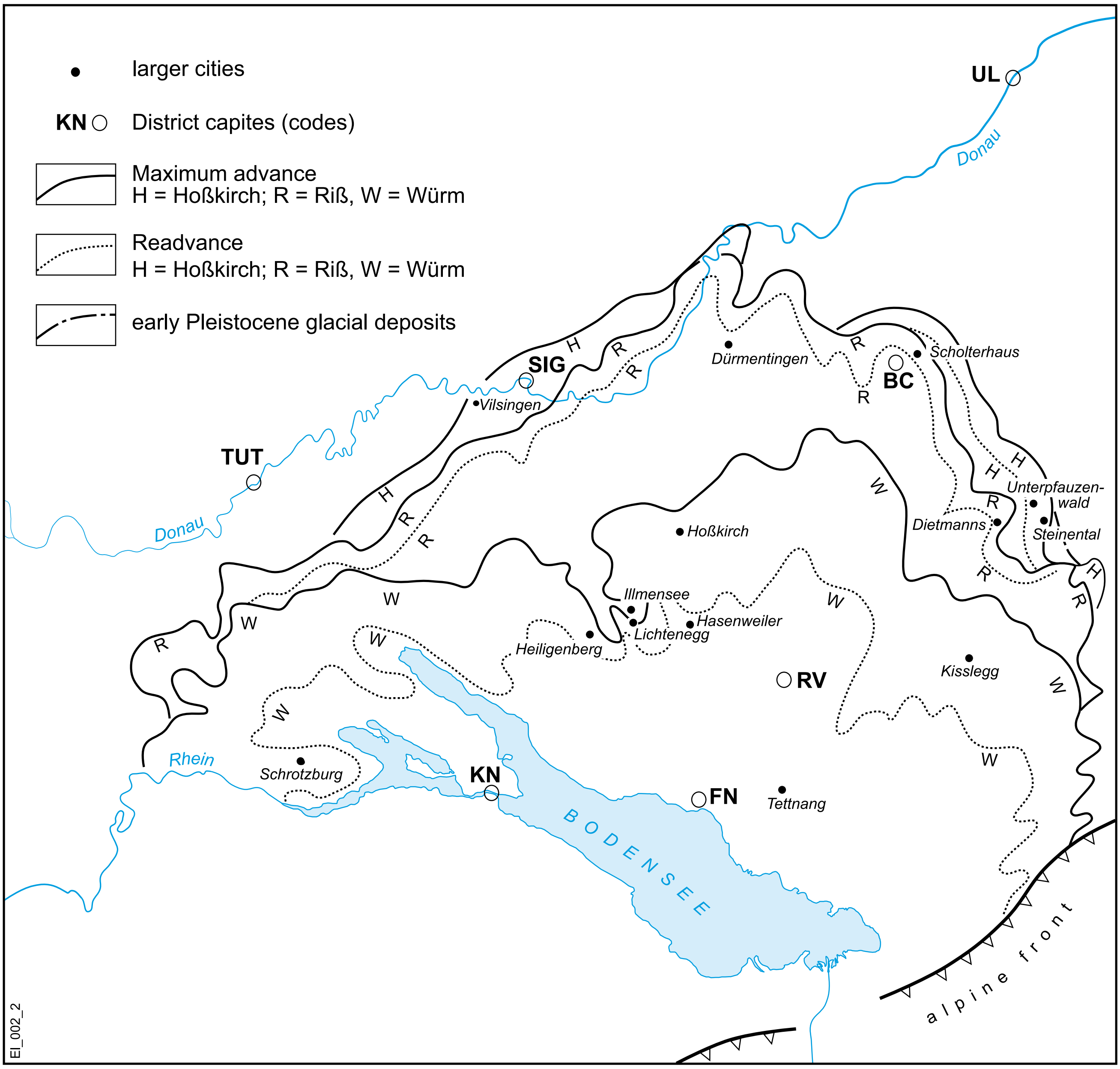

Fig. 1: Major cities and locations of the area between the Bodensee and Donau Valley, including locations referring to the formations and members of the new lithostratigraphical terms (ch. 4). – Also included are the major terminal moraine walls of the Rhineglacier; continuous lines: maximum advances of the Würmian (W), Rissian (R), and Hosskirchian (H) glaciations; dashed lines: readvances embracing glacially overdeepened basins. Cf. Fiebig 1995, 2003, LGRB 2005, Ellwanger 2003.

Abb. 1: Wichtige Städte in der Bodenseeregion und dem Donautal sowie die namengebenden Orte der neuen lithostratigraphischen Einheiten (siehe Kapitel 4). Die Hauptmoränenendwälle des Rheingletschers der Würm-, Riss- und Hosskirch-Eiszeiten sind als durchgezogene Linien dargestellt (W, R und H). Die Moränenwälle der Wiedervorstöße (gepunktete Linien) umranden die glazial übertieften Becken. Siehe hierzu auch Fiebig 1995, 2003, LGRB 2005, und Ellwanger 2003.

1 Introduction

The topography of the southwest German Alpine Foreland is the result of erosion (mainly of Tertiary bedrock) and deposition in the Quaternary (of mainly fluvial, glacial and lacustrine sediments). The major landforms were shaped by ice and meltwaters of the Rhineglacier in the Middle and Late Pleistocene. Before that, the area hosted several great rivers that are reconstructed using remnants of their fluvial sediments. Remnants of the eldest 'Deckenschotter' ('Donau-Deckenschotter') are found only in the nearby Bavarian and Swiss parts of the Alpine Foreland.

The area may be subdivided in four parts (Figs. 1, 2, 3):

- A deep "central foreland basin" (the 'Bodensee-Stammbecken') forms the core of the amphitheatre like modern topography. It is the prolongation of the overdeepened alpine Rhine Valley and surrounded by overdeepened "branch basins". All are filled with lacustrine sediments. There are highlands between the branch basins covered by drumlin moraines. An end moraine wall that represents a major readvance of the ice engulfs the branch basins and drumlin fields. Concentrically outside this inner moraine wall, a till plain with relics of the ice decay extend towards an outer end moraine. Principally the same holds for all

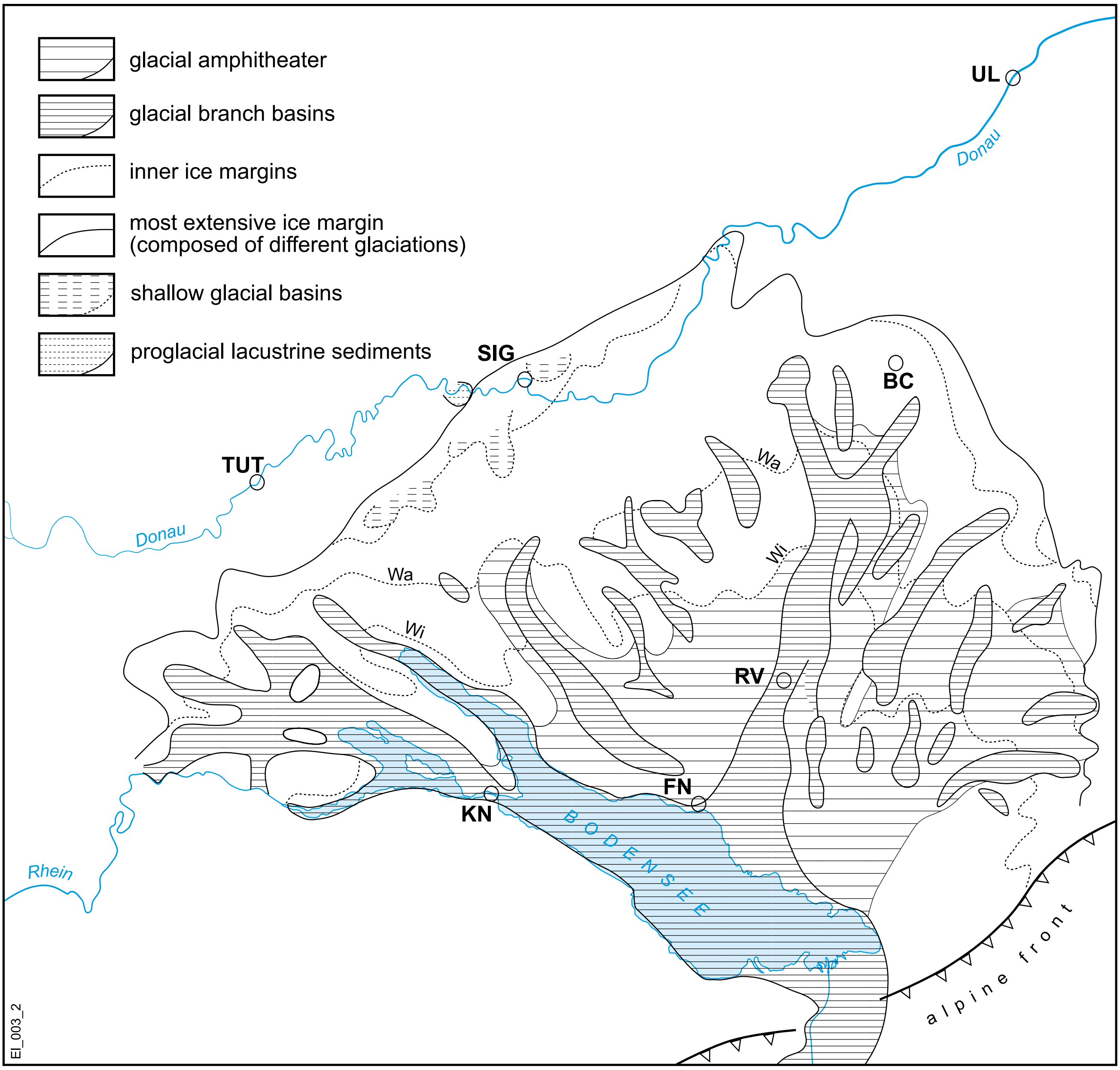

Fig. 2: Compilation of overdeepened basins of the Rhineglacier (north and west of the Bodensee) and the diachronous most extensive ice margin. Cf. Ellwanger *et al. 1995, 2011.*

Abb. 2: Zusammenstellung aller glazial übertieften Becken des Rheingletschers (nördlich und westlich des Bodensees) und der sich aus mehreren Gletschervorstößen ergebenden maximalen Eisbedeckung. Siehe hierzu Ellwanger *et al. 1995, 2011.*

three large foreland glaciations. The amphitheatre therefore results from the backstepping overdeepening towards the Alps in each glaciation.

- Northeast of the amphitheatre follows a series of fluvial terraces ('Iller-Riss-Platte') representing river and meltwater systems tributary to the Donau (Danube).

- Northwest of the amphitheatre there are elderly moraines with no or only shallow basins. Here, the alpine ice cover extended even beyond the Jurassic of the Swabian Alb.

- To the west, some deeply incised valleys are located in continuation of the central foreland basin. Deposits include moraines and gravels that further extend towards the Hochrhein Valley (between Basel and the Bodensee) and finally to the Upper Rhine Graben (URG).

The actual central basin hosts the Bodensee (Lake Constance), the largest lake north of the Alps. In some parts the base of Quaternary reaches down below sea level. This overdeepened surface has evolved from a pre-glacial, ramp-like topography with pre-alpine mountains and foothills and valleys of the alpine 'Deckenschotter' rivers. The present topography northeast and northwest of the amphitheatre still preserves a northern part of the ramp. The transformation of this ramp into the overdeepened topography is the "golden thread" of the Quaternary story of this area.

The transformation goes along with a hydrological reorientation of the area from the Donau system to the Rhine system i.e. from the Mediterranean to the North Sea. As an effect of the reorientation, each one of the three major glaciations has its own pattern of large landforms and sediment units. This is a "high-resolved" geomorphology that is often (not always) helpful to identify the stratigraphy of relief units (accommodation space) and sediment bodies (infill). This situation is unique, as in many other areas, the different ice advances keep following the same valleys.

East and west of the Bodensee amphitheatre, i.e. the Bavarian Alpine Foreland and the Swiss Midlands, the foreland topography is quite different. In Bavaria, wide fluvial gravel fields prevail, all directed towards the Donau. The glacial basins are smaller and located close to the alpine margin (Doppler et al. 2011). As opposed to this, the Swiss midlands were completely covered by ice. A mountainous topography prevails that includes Molasse highlands and strongly overdeepened valleys. This area is part of the Rhine system (Preusser et al. 2011).

Key areas for correlation with the Bavarian and Swiss Quaternary stratigraphy are the landsystems northeast and west of the Bodensee amphitheatre. I.e. the 'Deckenschotter' and meltwater terraces of the 'Iller-Riss-Platte' serve to correlate with the Bavarian terrace plains, as do the glacial basins towards the Hochrhein Valley to correlate with the Swiss midlands. An additional control is to use independent sedimentary evidence from its major sediment trap in the southern Upper Rhine Graben. To relate the special features of the neighbour regions with the high-resolved patterns of the Bodensee amphitheatre remains, up to now, a major challenge.

The actual chrono- and lithostratigraphy of the 'Bodensee-Oberschwaben' area is primarily based on three data sources: (1) the results of a century of geological mapping and research, (2) new key observations, (3) time markers. All data are evaluated focussing the actual chrono- and lithostratigraphical concepts and are summarized in a morphogenetical scenario.

Use of terms: Chronostratigraphy refers primarily to a (relative) time scale, lithostratigraphy to spatial correlation. Glaciation refers to ice advances in intervals of cold climate between interglacial periods.

2 The Basics: Observations and concepts

2.1 Traditional mapping and research

The stratigraphical tradition in the Alpine Foreland goes back to the first (and so far only) synopsis of the alpine Quaternary: Penck & Brückner's (1901/09) "circumalpine subdivision of the ice-age" (Die Alpen im Eiszeitalter) came out at the beginning of the 20th century. The four units 'Günz', 'Mindel', 'Riss' and 'Würm' were introduced that, ever since, were referred to as "alpine" units of the Quaternary.

Originally, the alpine units represented four terrace stages in prealpine valleys, i.e. this is a morphostratigraphical system referring to fluvial landforms:

- 'Niederterrasse' ('Würm', Late Pleistocene),
- 'Hochterrasse' ('Riss', Middle Pleistocene),
- 'Jüngere Deckenschotter' ('Mindel', Early Pleistocene),
- 'Ältere Deckenschotter' ('Günz', Early Pleistocene).

Penck & Brückner argued that the Würmian 'Niederterrasse' and the Rissian 'Hochterrasse' are correlated with adjoining (end-) moraines. They further argued that terraces outgoing from moraines were meltwater terraces. Both, moraines and terraces, were regarded as elements of a "glacial complex" ("Glaziale Serie"). Analogue to the Würmian and Rissian terraces, the 'Deckenschotter' terraces ('Günz' and 'Mindel') were also interpreted as elements of glacial complexes ('Glaziale Serien'). This is the basic consideration how the "tetra-glacial system of the alpine Quaternary stratigraphy" had been established.

In the decades to come, many authors have contributed to work out the alpine system in more detail. Primarily, additional terraces were identified, though on a more or less local level and definitely not "circumalpine". In parts of the Bodensee area, the four original units were mapped more precisely, some units were subdivided, new units added. Some deposits were even classified as 'Günz'- and 'Mindel' aged moraines. Additional terrace units permanently established were the 'Donau-Deckenschotter' (Eberl 1930, Löscher 1976) and the 'Biber-Deckenschotter' (Schaefer 1965). Following the system of the glacial complexes, they were both introduced as pre-'Günz'-glaciations of the so-called 'Ältestpleistozän' ("most early Pleistocene" or "earliest Pleistocene").

As correlation between the different gererations of units became more and more confusing, a "revision of nomenclature" was felt to be necessary. It ended up with a major re-interpretation of the 'Riss/Mindel', 'Mindel/Günz', and 'Günz/Donau' boundaries (Graul 1962, Schädel & Werner 1963).

After revision, more units were added: the 'Haslach-Deckenschotter' (between 'Günz' and 'Mindel', Schreiner & Ebel 1981, GLA 1995), the 'Jungriss'-Glaciation and the 'Saulgau'-Glaciation (both between Riss and Würm, Schreiner 1989, 1997, Frenzel 1991, cf. Habbe 1994, 2003, 2007). Again, the new units were only identified in few locations, but this lack of evidence was felt to be a lack of exposure or of thorough mapping. In an effort to cover possibly still unidentified units in all places, the concept of complex-units was introduced. The latest terms include 'Würm-Komplex', 'Riss-Komplex', 'Mindel-Komplex' (or 'Haslach-Mindel-Komplex'), 'Günz-Komplex', 'Biber-Donau-Komplex' etc.

All this is only a rough summary of the history of the morphostratigraphical terms and concepts, to illustrate some of the pitfalls to be avoided when using all these highly valuable data from elderly sources. This includes the use of the geological maps in scale 1:25.000: Its last sheets have recently been completed using the latest generation or terms, but production of the first sheets had started even before Penck & Brückner's circumalpine nomenclature was established. I.e. this dataset includes almost all the above add-ons, revisions and subdivisions.

In our actual approach, many results of the morphostratigraphical maps and papers are further used after being transformed accordingly. This includes terminal moraines, patterns of terrace stratigraphy, but also features related to the relief as fossil soil successions or periglacial sediment covers ("pedostratigraphy"). Some large relief elements, e.g. glacial basins serving as major sediment traps, are now much more focussed upon than before. Other elements of the morphostratigraphical approach had to be re-interpreted or even abandoned. This includes the use of Penck's "glacial complex" regarding the 'Deckenschotter'

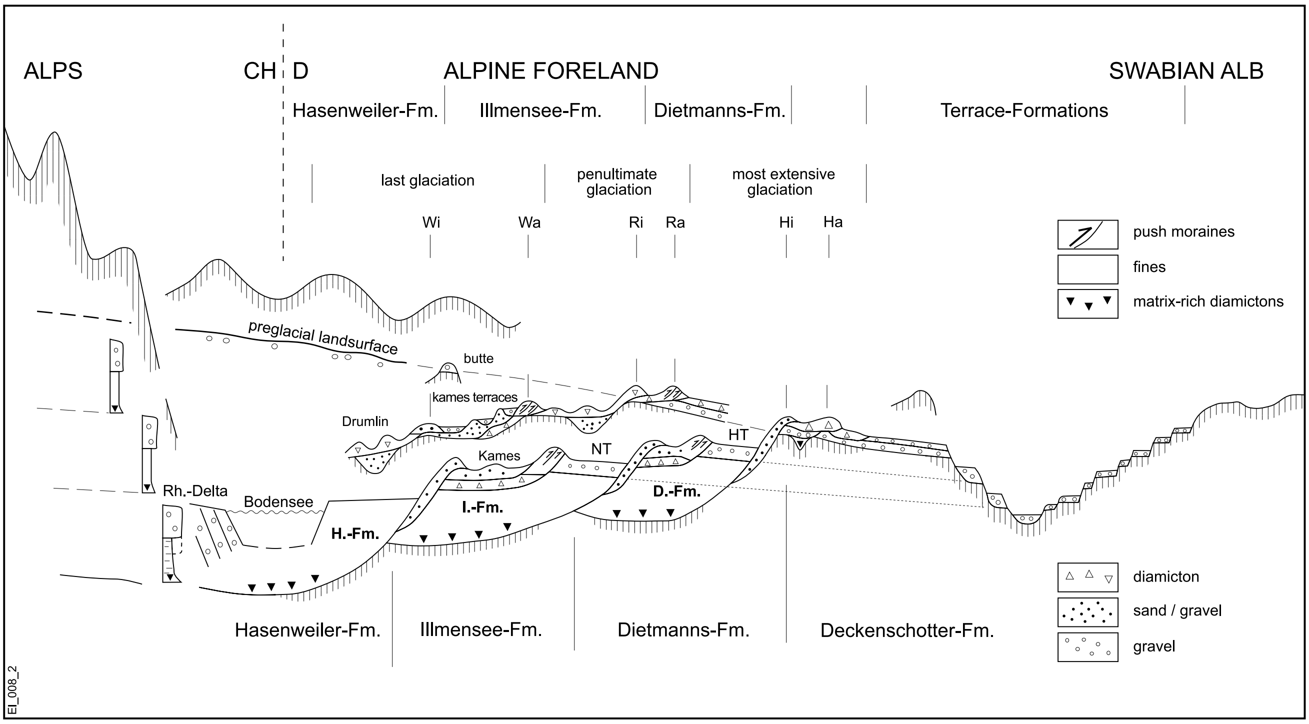

Fig. 3: Schematical cross section of the amphitheatre of the Bodensee area, from the alpine front in the south, to the terrace-landscape and Donau Valley in the north: – Top, 3rd backdrop: surface of the former foothills in the Early Pleistocene (Gelasian super stage), acting as watershed between the Bavarian 'Donau-Deckenschotter' and the Swiss 'Höhere Hochrhein-Deckenschotter' i.e. between the valleys of Donau and Rhine. – Upper middle, 2nd backdrop: niveau of an Early Pleistocene 'Deckenschotter' valley (Calabrian super stage), representing the evolving valley of the alpine Rhine. – Lower middle, 1st backdrop: Bodensee amphitheatre, niveau of the surface of three generations of Middle and Late Pleistocene highs between glacial basins (Hasenweiler-, Illmensee-, and Dietmanns-Fm.), covered by drumlins, kames, kame terraces etc. – Front (main section): Bodensee-amphitheatre, niveau of the surface of three generations of overdeepened glacial basins (Dietmanns-, Illmensee- and Hasenweiler-Fm.) The actual Bodensee marks the central basin where deposition is still ongoing. – North of the amphitheatre, the "old surface" of the Early Pleistocene 'Deckenschotter' is only modified by fluvial erosion shown by fluvial terrace levels towards the Donau Valley.
This landsystem exhibits an overall negative sediment budget. Its thickest and best-resolved sediment successions are hosted within the overdeepened glacial basins. Together with correlative terminal moraines (of the readvances of the Hosskirchian = Hi, Rissian = Ri, and Würmian = Wi stages), the unconformities are used to subdivide the sediment succession into formations. Cf. Fiebig 1995, 2003, LGRB 2005, Ellwanger 2003, Ellwanger et al. 2011.

Abb. 3: Schematischer Schnitt durch das Amphitheater des Bodenseegebiets von den Alpen im Süden (links) bis zur Terrassenlandschaft des Donautals im Norden (rechts): – Oben, 3te Kulisse: Ehemalige Vorberge des Unteren Pleistozän (Gelasium). Sie trennten als eine Wasserscheide die Abflüsse Richtung Donau und Rhein und somit die Donau-wärtigen Deckenschotter Bayerns von den „Schweizer" Höheren Hochrhein-Deckenschottern. – Obere Mitte, 2te Kulisse: Niveau des unterpleistozänen Deckenschottertales (Calabrium), des sich entwickelnden Alpenrheins. – Untere Mitte, 1te Kulisse: Bodensee Amphitheater, Schnitt durch die Hochgebiete des Mittleren und Oberen Pleistozän (drei Generationen: Hasenweiler-, Illmensee-, und Dietmanns- Formationen) zwischen den Glazialbecken; Die Landshaft ist geprägt von Drumlins, Kames und Kamesterrassen etc. – Vorne (Hauptschnitt): Bodensee-Amphitheater, Schnitt durch die übertieften Glazialbecken der Dietmanns-, Illmensee- and Hasenweiler- Formationen) Der Bodensee selbst stellt das zentrale Becken der letzten Vergletscherung dar, in dem die Ablagerung unvermindert fortdauert. – Nördlich des eigentlichen Amphitheaters wird die „alte" Oberfläche der frühpleistozänen Deckenschotterlandschaft nur durch fluviale Erosion überprägt, was sich in den Flußterrassen Richtung Donautal ausdrückt.
Dieses Landschaftssystem ist durch ein generell negatives Sedimentbudget charakterisiert. Die Glazialbecken enthalten die mächtigsten und hochauflösendsten Sedimentabfolgen. Die basalen Diskontinuitätsflächen und ihre zugehörigen Endmoränen (der Wiedervorstöße der Hosskirch = Hi, Riss = Ri, und Würm = Wi Eiszeiten) werden herangezogen um die Abfolgen in Formationen zu gliedern. Siehe auch Fiebig 1995, 2003, LGRB 2005, Ellwanger 2003, Ellwanger et al. 2011.

units and the position of some stratigraphical boundaries.

The first steps towards lithostratigraphy were the observations of Schädel (1950, 1953) that the 'Deckenschotter' gravels in the Bodensee area differ not only in position, but also in petrographical composition: He found out that the higher niveaus are poor in crystalline pebbles (< 5 %) but rich in dolomite (highest terrace, e.g. 'Donau'-aged), respectively rich in helvetic limestones (middle level, e.g. 'Günz'-aged). Only the 'Mindel'-aged gravels of the lowest terrace are rich in crystalline (> 10 %, sometimes up to 35 %). Obviously, this reflects differences in sediment provenance.

2.2 New key observations and re-interpretations

Improved information on Quaternary sediments became available as drilling activities increased. Cores and samples come from both, research projects and studies of Applied Geology (e.g. Hydrogeology, Raw Materials, Engineering Geology). The identification of the geometry of sediment bodies and the correlation of sedimentary units were used to supplement the traditional morphostratigraphical correlation. To make Quaternary stratigraphy serve as a correlation tool further on, an updated system will have to focus more strongly on sediments, i.e. it has to be shifted towards lithostratigraphy. The mere inclusion of drilling results into the old concepts is not enough; we strongly believe that some conceptual re-adjustments are also inevitable.

The basic considerations are:

- More emphasis than before is given to Penck & Brückner's basic distinction of 'Deckenschotter' (Günzian, Mindelian) and "terrace gravels" (Rissian, Würmian). Terrace gravels are related to large foreland glaciations where terminal moraine walls and other morainic landforms and sediments are hosted in an amphitheatre topography that also includes the overdeepened glacial "branch-" basins. There is no evidence of a likewise overdeepened topography related to the 'Deckenschotter' units. They are suggested to represent an alpine fluvial system (Fig. 2 and Fig. 8) that is preserved in buttes, large gravel-filled channels and gravel terraces (Fig. 3 and Ellwanger 2003).

- A series of deep core drillings into the glacial basin of Hosskirch (Fig. 1) revealed sub- and proglacial deposits grading up into interglacial deposits of Holsteinian age at the bottom of the basin, well below of a butte of 'Mindel-Deckenschotter'. Here, a new major alpine glacial unit had to be introduced between the 'Mindel-Deckenschotter' and the Rissian unit (Ellwanger et al. 1995, Ellwanger 2003). It has been labelled 'Hosskirch glaciation'. Hosskirchian glacial and periglacial sediments were also mapped elsewhere: either outside of the Rissian terminal moraines, or beneath the Rissian till sheets. Alike to the setting of the 'Hosskirch' Basin, the stratigraphical identification of Hosskirchian sediments is best if a Holsteinian time marker is available. – Including the Hosskirchian unit, there is evidence of three major glaciations in the Bodensee area (Hosskirchian, Rissian, Würmian).

- All three major glaciations (Würmian, Rissian, Hosskirchian) turn out to be twincycles (Figs. 1 & 4) that include two major ice advances (Fiebig 1995, 2003, STD 2002). Each advance is represented by (Fig. 3) a till sequence, sometimes associated with other sediments of advancing and/or downmelting ice. The overdeepened basins usually contain a succession of glaciolacustrine, lacustrine and peri- to postglacial deposits; they clearly indicate the final downmelting of the ice (there is no subglacial till). There are three types of assemblages: (a) bold terminal moraines (often push moraines) associated with a till sequence that is dominated by sands and gravels of downmelting stagnant ice (kames and eskers), (b) terminal moraines associated with drumlinized till (drumlin fields) featuring advancing ice, and (c) terminal moraines more or less closely engulfing the overdeepened basins (their infill again featuring downmelting). The terminal moraines in (b) and (c) represent the same ice advances.

- The major erosion is a matter of huge sediment discharge from inside and outside of the alpine margin. The mass deficit has to be complemented with a mass surplus elsewhere. The Upper Rhinegraben (URG) serves as the first major sediment basin of the Rhine system between the Alps and the North Sea. At its southern end is a huge fan of alpine debris. Here, numerous drillings reveal a sediment succession that includes in its upper part two impressive horizons with coarse components in a poorly sorted matrix. They are suggested to be correlative with the basin erosion unconformities of the glacial basins at the alpine margin, reflecting the high sediment transport dynamics of the erosion events (erosion-accumulation-systems, Ellwanger 2003). This scenario is directly applied for the last and penultimate glaciation. Regarding the prepenultimate generation of glacial basin (Hosskirchian), the correlative sediment patterns in the Upper Rhine Graben (URG) become more complicated. There was probably less sediment input from the Rhine Glacier (that was still more directed towards the Donau valley), and increased subsidence (in the URG) and uplift (at the margin) have to be considered (e.g. Gabriel et al. 2008).

- The correlation of basin erosion events with the coarse horizons in the URG implies huge sediment volumes to be transferred through the Hochrhein Valley in a short time. In this process, the valley suffered strong morphogenesis. Large terrace levels were created mainly by erosion. Only in some wide parts of the valley, accumulation sporadically continued, e.g. the massive coarse horizon in Wyhlen (cf. Geotop Wyhlen 2007). There are two main terrace levels ('Hochterrasse', 'Niederterrasse'). Their gravel bodies are often composed by multiple gravel cycles that may even comprise quite elderly accumulation periods, e.g. of older glacial cycles. If at all, only the terrace surfaces may be considered as element of a "glacial series", not the gravel body.

Combining the above with the "traditional" approach to Quaternary forms and sediments, the distinction between glacial and non-glacial sedimentary environments (i.e. fluvial, lacustrine) becomes more specific. Not only the 'Deckenschotter' gravels, but also parts of the Middle and Late Pleistocene terrace gravels are now considered to be of fluvial i.e. non-glacial origin. This is a major difference to the classical concept still using the "glacial series". We now interpret fluvial sediments as fluvial sediments, and not as an indirect proof of a glacial source; this is less hypothetical than the classical approach. In consequence, a glacial setting now has to be primarily identified by subglacial deposits (e.g. till).

The above results may be combined with time markers to set up a chronostratigraphical system updating the traditional morphostratigraphy, or they may be used to establish a lithostratigraphy of unconformity-bounded sediment units. The latter would be basically a sequence stratigraphic approach that also includes the potential to predict certain features, as sediment successions or the range of future ice advances. Both systems are "state-of-the-art"; it depends on the issue to be solved, which is more appropriate.

2.3 Time markers

The incorporation of time markers is inevitable in chronostratigraphy and quite helpful to control correlation in lithostratigraphy. The time markers used here come from biostratigraphy and palaeomagnetism; they comprise the "European Neogene Mammal Zone 17" (MN17), the pollen assemblages of the north-west-European warm periods of the Bavelian, the Holsteinian and the Eemian, and the Matuyama Epoch of the palaeomagnetic record.

For various reasons, physical age estimates, e.g. luminescence datings (OSL), are not included. That is because, up to now, there are too few "state of the art" studies delivering reliable physical ages of the Rhineglacier area, to be competitive with the biostratigraphical markers. Still we quote some actual studies of different units as examples:

- Würmian: luminescence datings by Kock et al. (2009) and Frechen et al. (2010) deliver inconsistent ages although identical samples were taken ('Niederterrassenschotter', Hochrhein-valley).

- Rissian: luminescence dating by Dehnert et al. (2010), Swiss midlands, discussed by Preusser et al. (2011).

- Holsteinian: luminescence dating by Klasen (2008) and the palynological interpretation by Müller (2001) may or may not be consistent, depending on the "absolute" age of the Holsteinian" (cf. discrepancy of STD 2002 and Cohen & Gibbard 2010).

- 'Deckenschotter': burial age dating by Häuselmann et al. (2007). This study refers to 'Deckenschotter' in Bavaria, further discussed by Doppler et al. (2011).

The "absolute" ages will be needed to estimate sedimentation rates or transport volumes. Presently we use the STD (2002) to transform biostratigraphical markers and sediment units into a geochronological frame (e.g. Neeb et al. 2004). In this way some preliminary estimates of sedimentation rates can be achieved already today. Any more detailed quantitative scenario will need a more accurate time frame.

The stratigraphical markers used here are listed in the context of their sediment succession and interpreted with regard to the chronostratigraphy of the sediments (locations cf. Fig. 1).

2.3.1 Neogene Mammal Zone MN 17

The MN 17 marker is known from a series of overbank fine sediments overlying some of the eldest 'Deckenschotter' remnants east and west of the Bodensee area in the Bavarian and Swiss Alpine Foreland: In Bavaria the 'Uhlenberg-Deckenschotter' ('Biber-Donau-Deckenschotter', cf. Schädel 1950, Ellwanger, Fejfar & von Koenigswald 1994, Doppler & Jerz 1995, Doppler 2003), in Switzerland the 'Irchel Deckenschotter' ('Höhere Deckenschotter', cf. Verderber 1992, 2003, Graf 1993, 2009, Bolliger et al. 1996). Accordingly the 'Donau'-aged 'Deckenschotter' represents the Gelasian super-stage of the Early Pleistocene (STD 2002, Cohen & Gibbard 2010).

2.3.2 Pollen assemblages

2.3.2.1 The Early Pleistocene pollen sequence of Unterpfauzenwald

The peat of Unterpfauzenwald ("Iller-Riss-Platte" near Leutkirch) is associated with an isolated till unit. The sediment succession begins with a gravel-unit of crystalline-poor 'Ältere Deckenschotter' with a weathered palaeosol-surface. Next follows a lower till sequence grading into fines and a peat containing the pollen flora. One or two till sequences of an upper till unit and strongly weathered periglacial sediments cover the peat. Both till-units contain > 10 % of crystalline pebbles i.e. they postdate the crystalline-poor 'Ältere Deckenschotter'.

(4) Periglacial fine sediments, strongly weathered;
(3) Upper till unit;
(2) Lower till unit grading into peat, pollen assemblage;
(1) Gravel of 'Ältere Deckenschotter', palaeosol.

The pollen assemblage includes *Tsuga*, *Pterocarya* and *Ostrya* that allows for correlation with the Early Pleistocene Bavelian stage (Hahne et al. 2010). An earlier interpretation by Göttlich (1974) suggested a Holsteinian age that is not compatible with *Tsuga* and *Ostrya*. W. Bludau suggested an age "Cromerian or older" (Bibus et al.1996).

Accepting the correlation with the Bavelian, the lower till unit represents an Early Pleistocene ice advance, either as cold period within the Bavelian or as an equivalent of the northwest European Menapian cold stage.

2.3.2.2 Holsteinian Pollen assemblages

Pollen assemblages that are attributed to the Holsteinian interglacial period were identified in various deep basins of the first generation, but also in some shallow basins and, in one case, within a gravel succession formerly attributed to the penultimate glaciation. The pollen assemblages include *Abies* almost continuously in various values, and in many cases (not always) *Fagus & Pterocarya* in the upper part of the succession (Hahne 2010).

In the deep basins, the succession usually begins with diamicton grading up into glaciolacustrine fine sediments with few pebbles (dropstones) and further up into laminated and massive lacustrine fines. This is where the pollen faunas usually occur. Depending on the position of the basin, the fines may be covered by glacial sediments or by meltwater sediments of the next younger glaciation.

(4) Sediments of the penultimate glaciation (Rissian), e.g. till or meltwater sediments;
(3) Lacustrine fine sediments, Holsteinian pollen assemblage;
(2) Glaciolacustrine sediments of the prepenultimate glaciation (Hosskirchian);
(1) Diamicton.

This kind of sediment succession including reliable Holsteinian pollen assemblages was identified in the glacial basins of Tannwald and Hosskirch (det. Bludau, Ellwanger et al. 1995, cf. Hahne 2010). In the Singen Basin (det. Bludau, Hahne 2010) the pollen-rich sediments were more sand-dominated and are probably less reliable (see Fig. 7). Also in the Waldburg basin Holsteinian pollen assemblages were found, but, in this case, not in a succession proper (Fiebig 1995).

Another reliable Holsteinian pollen flora is described from the "shallow basin" at Bittelschiess (Bludau in Schirmer 1995, Bibus & Kösel, 1996, Müller 2001, outcrop evolution cf. Ellwanger et al. 2011). It occurs within the finegrained bottom sets of an otherwise gravely delta unit. Another Holsteinian datum comes from fluvial gravels at Schmiecher See (det. Grüger 1995, cf. Hahne in Ellwanger, Simon & Ufrecht 2009).

2.3.2.3 Eemian Pollen assemblages

Only few Pollen assemblages that are attributed to the Eemian interglacial have yet been detected in the second generation of deep glacial basins. Best in the area of the Rhineglacier is the succession in the deep glacial basins of Bad

Wurzach (Wurzach Basin, Grüger & Schreiner 1993) that includes, beside of the Eemian, a succession of interstadials of the early and middle Würmian. Two Eemian deposits are reported from the Hosskirch Basin (det. Bludau, Ellwanger et al. 1995, Hahne 2010), and from the Singen Basin (det. Bludau, Szenkler, Bertleff, & Ellwanger 1997, and Szenkler & Bock 1999).

Most Eemian deposits are from shallow intramoraine basins on the till plains of the penultimate glaciation. They are usually not covered by till, though some controversies still remain open. Examples are the shallow basins from Krumbach (Frenzel & Bludau 1987), Füramoos (Müller 2001) and Jammertal (Müller, 2000)

2.3.2.4 Holocene Pollen assemblages

The infill of the last generation of glacial basins ends up with fine sediments that are commonly believed to represent the Holocene. This is usually not controlled but has exemplarily been verified in the Hasenweiler Basin (det. Knipping).

2.3.3 The palaeomagnetic records of Lichtenegg and Altheiligenberg

2.3.3.1 Lichtenegg

The succession of till and lacustrine sediments at Lichtenegg and at Schienerberg are the only two sites in the Rheinglacier area where glacial deposits follow after, and are overlain by gravels of the 'Deckenschotter' (for the 'Jüngere Deckenschotter' at Schiener Berg cf. Schreiner 2003 and Graf 2009).

There are several descriptions of the unique sediment succession of Lichtenegg that include a discussion of the palaeomagnetical results (Ellwanger et al. 1995, Ellwanger, Fiebig, & Heinz 1999, Bibus & Kösel 2003). A detailed description of the lithofacies is provided by Menzies & Ellwanger 2010. The succession starts with about 5 m of grey and brown gravels, sand and fines (including up to 10 % of crystalline pebbles). It is followed by several sequences of almost steel-grey subglacial and glaciolacustrine till (30–40 m), grading into lacustrine sediments (20 m). With an unconformity a brown sand-dominated succession with a palaeosol follows and is overlain by still another till sequence (15 m). Another unconformity follows as basis of quite coarse gravels (8 m). They are finally overlain by a package of > 20 m of massive gravels, very coarse and quite proximal ('Jüngere' = 'Mindel-Deckenschotter').

Analyses of the magnetic orientation of some fine-grained layers come to the result that several reliable samples are inversely magnetised (Fromm 1989, Rolf 1992). Although some questions regarding subglacial and diagenetic deformation are still in discussion, the sediment succession should be deposited in a period of inverse magnetic polarity, probably the Matuyama epoch.

2.3.3.2 Altheiligenberg

The deposits at Altheiligenberg represent the upper part of the crystalline-poor 'Heiligenberg Schotter' that is clearly appertained to as 'Älterer Deckenschotter' (Schädel 1950, Ellwanger et al. 1995). At Altheiligenberg, the gravels alternate with some sand- and silt-dominated horizons. Their magnetic orientation was again analysed by Fromm (1989) and Rolf (1992). The samples from the silt-horizon showed clearly an inverse magnetisation and probably also represent the Matuyama Epoch.

2.3.3.3 Summary of the time markers

The presently available time markers, as relevant of the Bodensee area, are subsumed in Tab. 1: They represent the Gelasian and Calabrian stages of the Early Pleistocene, the Holsteinian of the Middle Pleistocene, the Eemian of the Late Pleistocene and the Holocene. No evidence of the Cromerian stage of the early Middle Pleistocene has yet been recorded.

3 Chronostratigraphy of the Quaternary of the Rhineglacier area

Following Litt (2007, et al. 2005) and STD (2002), the definition of chronostratigraphical units (stages) of the Quaternary can be based upon the glacial-interglacial patterns, terrace stratigraphical levels (morphostratigraphy) and time markers. In the Bodensee area this leads to a succession as shown in Tab. 1 (right column). The basic division again subsumes two elements: an elderly system of Early Pleistocene alpine river gravels ('Deckenschotter'), and a younger system of foreland glaciations of the later Middle and Late Pleistocene. There is a gap in the early Middle Pleistocene as no evidence of sediments of this time slice has yet been identified in the Bodensee area (Tab. 2). This pattern follows the classical scheme of Penck & Brückner (1901/09), who describe a "great interglacial" (Grosses Interglazial) in the position of the gap.

Going into more detail, the 'Deckenschotter' and the "great glaciations" are further differentiated relying on morphostratigraphy: In case of 'Deckenschotter' supplemented by sediment petrography, in case of the glacial deposits by typical lithofacies successions. In both cases, the classification is controlled by time markers (Tabs 1 & 2).

3.1 Early Pleistocene 'Deckenschotter' (alpine river system)

There are three 'Deckenschotter' units: The 'Donau-Deckenschotter' ('Biber-Donau'), the 'Günz-Deckenschotter', and the 'Mindel-Deckenschotter' (Tab. 1). As outlined above, their identification refers to morphostratigraphy and petrographical composition. The yet available 'Deckenschotter' time markers refer to the record of the Neogene Mammal Zones, the palaeomagnetic record, and the palynostratigraphical record.

The Bavarian 'Donau-Deckenschotter' ('Ältestpleistozän', 'Eopleistozän', earliest Pleistocene), and the Swiss 'Irchel Deckenschotter', host the Mammal Zone MN 17 that represents the Gelasian stage, formerly late Pliocene, now Early Pleistocene (STD 2002, Cohen & Gibbard 2010).

The inverse magnetic inclination from Altheiligenberg and Lichtenegg suggests that the 'Günz' stage and the

Tab. 1: Time markers (2.3) and local chronostratigraphical stages (3) of the Bodensee area (in brackets '()': not recorded).

Tab. 1: Zeitmarken (2.3) und lokale chronostratigraphische Stufen (3) der Bodenseeregion (in Klammern '()': nicht überliefert).

			Time markers			Chronostratigraphy of the Bodensee area	
Standard Stages			Palynostratigraphy	Mammal Zones	Palaeomagnetics		
Holocene							
Pleistocene	Late	Tarantian		(MNQ1)	(Brunhes)	Glacial and inter-glacial units (stages)	Würmian
			Eemian				Eemian
	Middle	Ionian					Rissian
			Holsteinian				Holsteinian
							Hosskirchian
			(Cromerian)				
	Early	Calabrian	Bavelian		Matuyama	Great alpine rivers Deckenschotter	Jüngere Deckenschotter (Mindel)
			(Menapian)				
			(Waalian)				Ältere Deckenschotter (Günz)
			(Eburonian)				
		Gelasian	(Tiglian)	MN 17			Älteste Deckenschotter (Donau)
			(Pretiglian)				

Tab. 2: Comparison of chronostratigraphical terms used in Switzerland, Bavaria and Baden-Württemberg; formerly used terms in brackets '()'.

Tab. 2: Vergleich der chronostratigraphischen Begriffe der Schweiz, Bayerns und Baden-Württembergs; früher verwendete Begriffe stehen in Klammern '()'.

Chronostratigraphy		Swiss alpine foreland	Bodensee area	Bavarian alpine foreland
Late Pleistocene		Last Glaciations / LGM / Birrfeld	Würmian	Würm (-Komplex)
		Eem sensu Welten	Eemian	Eem (Riss/Würm-Interglacial)
Middle Pleistocene		Penultimate Glaciation / Koblenz	Rissian	Riss (-Komplex)
		Meikirch-Interglacial		
		Habsburg		
		Holstein Pterocarya	Holsteinian	Holstein (Mindel /Riss-Interglacial)
		Major Glaciation	Hosskirchian	Mindel
	Cromerian			Günz/Mindel-Interglacial
		MEG / Möhlin		Günz
Early Pleistocene (Calabrian)		Morphotectonic Event		
		Tiefere Deckenschotter	(Jüngere) Mindel-Deckenschotter	Donau
			(Ältere) Günz-Deckenschotter	
		Höhere Deckenschotter	(Älteste) Donau-Deckenschotter	
				Biber

'Mindel' stage are part of the Matuyama epoch (Fromm 1989, Rolf 1992). They postdate the 'Donau-Deckenschotter' representing younger intervals of the Early Pleistocene. This is supported by the identification of the Bavelian warm period in the peat of Unterpfauzenwald. The peat overlies an isolated deposit of crystalline-rich till ('Mindel' stage, Tab. 1). This view corresponds well with the stratigraphical classification by Graf (2009) of "upper and lower" 'Deckenschotter' of Switzerland, but is opposed to the interpretation of the 'Deckenschotter' of the Bavarian Alpine Foreland according to which the 'Mindel' stage and part of the 'Günz' stage are already part of the Middle Pleistocene (Doppler 2003).

The chronostratigraphy of the 'Deckenschotter' interval as suggested here (Tabs. 1 & 2) seems conclusive, also regarding available time markers. It covers the Early Pleistocene in poor resolution, but this is not surprising in a terrace stratigraphical setting that is primarily controlled

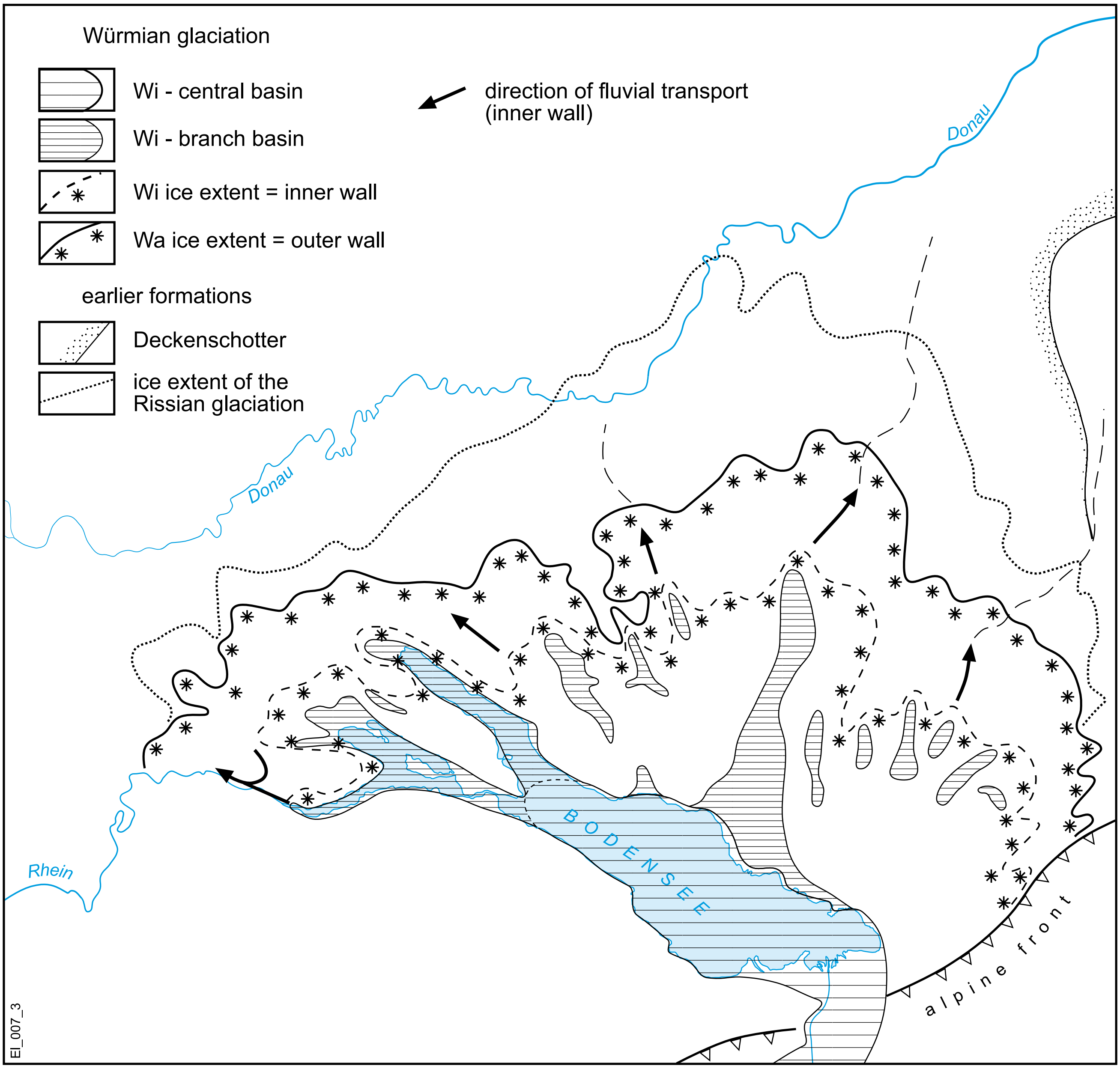

Fig. 4: Endmoränen und Glazialbecken der Würm-Eiszeit als ein Beispiel für glaziale Doppelzyklen: Das übertiefte Bodenseebecken im Zentrum und davon radial ausgehende langgestreckte Zweigbecken, die vom Endmoränenwall des Würm-Wiedervorstoßes umrahmt werden. Die tiefeingreifende Beckenerosion entsteht beim Wiedervorstoß. Dagegen bedeckt der Gletscher des ersten Vorstoßes zur Äußeren Würmendmoräne (Wa) eine wesentlich größere Fläche. Siehe hierzu auch Fiebig 1995, 2003, Ellwanger et al. 2011.

Abb. 4: Terminal moraines and glacial basins of the Würmian stage, as an example of a twincycle glaciation: The overdeepened Bodensee Basin in the centre, radially embraced by elongated branch basins that are encircled by the terminal moraine wall of the Würmian readvance. Deep basin erosion corresponds to this readvance. Whereas the first Würmian ice advance to the outer Würmian moraine (Wa) covered a much wider area. Cf. Fiebig 1995, 2003, Ellwanger et al. 2011.

by tectonics. A far better resolution of this time slice has been identified in the nearby Heidelberg Basin of the Upper Rhine Graben (Gabriel et al. 2008).

3.2 Middle and Late Pleistocene ice advances of the Rhineglacier

The chronostratigraphical record of the Middle and Late Pleistocene glaciations of the Rhineglacier comprises the three "glacial" stages Hosskirchian, Rissian and Würmian, and the "interglacial" stages Holsteinian and Eemian (their palynological records also serving as time markers). In geological mapping the sediment surfaces are also differentiated by the thickness of their cover of weathered and periglacial sediments (Schreiner & Haag 1982, Bibus & Kösel 1996). The cover averages about 1 m overlying Würmian sediment surfaces, about 2–3 m including the "Eem" fossil soil in the Rissian and about 3–4 m or more including several fossil soils in pre-Rissian surfaces.

All three glacial units are composed of sediments of two major ice-advances. Their extend is marked by an outer and an inner wall of terminal moraines (twin-cycle, cf. Fiebig, 1995, 2003, STD 2002). Each of the ice margins engulfs a glacial landsystem of different subglacial to proglacial sediments and landforms (Fig. 4): within the margin of the first ice advance (usually the outer = "maximum" margin), elements of downmelting ice prevail at the land surface, as eskers, kames and kames terraces. They are best preserved in the Würmian = last glacial maximum, LGM. Within the margin of the readvance there are two different systems of sediments and landforms: one is primarily related to active ice (frequently drumlins), the other subsumes the deeply incised glacial basins and their sediment infill (Fig. 3).

In spite of their highly resolvable erosion and sedimentation patterns, the two advances of the twin-cycles are subsumed in only one substage in the chronostratigraphical record (e.g. late Würmian, 'Oberwürm'). This substage marks the culmination of a series of earlier cold-warm variations that have far less effects regarding erosion and sedimentation (e.g. the substages of the early and middle Würmian, Grüger & Schreiner 1993). Most of the cold phases of the record are considered to represent periglacial cold climate, but some were also suggested to possibly represent additional ice advances (cf. Frenzel 1991, LGRB 1995, 2002, STD 2002; "single cycles" sensu Fiebig 1995, 2003).

This "state-of-the-art" chronostratigraphical scheme goes well beyond the classical glacial/interglacial scheme as introduced by Penck & Brückner (1901/09), in spite of the continuous use of the terms 'Riss' and 'Würm' that were originally more closely focussed upon sediments and landforms (morphostratigraphy). However, the refocus of the morphostratigraphical approach towards chronostratigraphy was also initiated by Penck & Brückner introducing an early 'Würm' oscillation called 'Laufenschwankung'.

3.3 Chronostratigraphical summary

The stratigraphical succession of the Early, Middle and Late Pleistocene begins with the Early Pleistocene 'Deckenschotter'. They are interpreted in terms of an alpine fluvial system. Its terrace patterns and lithology are suggested to reflect the changing local palaeotopography, not climate, and it contains huge hiatuses. The oldest yet known till deposits of an early Rhineglacier are related to the "youngest" 'Deckenschotter' subunit ('Mindel').

The Middle and Late Pleistocene comprise three glacial units in post-'Deckenschotter' position, Hosskirch, Riss und Würm. Each unit shows good evidence of two ice advances of the Rhineglacier. The interglacial record comprises the Holsteinian, the Eemian and the Holocene (Tab. 1).

The Quaternary chronostratigraphy of the Rhineglacier area as presented here is in parts quite different from systems used in neighbouring areas. The main differences concern the early Middle Pleistocene time interval. Here, a hiatus is suggested in the Rhineglacier area, which is correlated with various stratigraphical units in the schemes of Bavaria and Switzerland (Tab. 2):

- In the Bavarian scheme, the early Middle Pleistocene is represented by the 'Günz'-, 'Haslach'- and 'Mindel-Deckenschotter' (Doppler 2003). The transition from 'Deckenschotter' units to the Rissian stage (elderly moraines and high terraces, "Hochterrasse") is marked by the Holsteinian interglacial stage (Samerberg II, Grüger 1983).

- In the Swiss scheme, the early Middle Pleistocene is represented by the "most extensive" and the "extensive" glaciation. Here, the transition from 'Deckenschotter' to the glaciations is marked by a "morphotectonic event", probably still in the Early Pleistocene (Preusser 2009, Graf 2009).

Obviously, the schemes of Bavaria and Switzerland reflect extreme positions that will be difficult to correlate with each other. The Rhineglacier chronostratigraphical scheme comes almost as a compromise between the extremes, but it is primarily an attempt to meet the different evidences of the Bodensee area.

To resolve the highly differentiated sediments and landforms of the three twincycle ice advances, the twincycle substages are often subdivided into a couple of lithofacies units (e.g. the late Würmian = 'Oberwürm' substage in the geological map 1:25.000 sheet 8225 Kisslegg). Here, an approach might be more consistent that is based on a lithostratigraphical scheme.

4 Lithostratigraphy and lithostratigraphical definitions of the Quaternary of the Rhineglacier area

The lithostratigraphical division of the Quaternary of this area is designed to define and correlate geological units primarily based upon sedimentary features. With regard to the negative sediment budget of the Alpine Foreland, the sediment units are unconformity-bounded. Their first order unconformities are the major erosion surfaces that cause the deepening of the landsystems at the alpine margin, their second order unconformities are related to ice advances or large fluvial terrace-systems.

Following the recommendations of Steininger & Piller (1999) and LGRB (2005), the "formation" (Fm.) serves as the central unit in the lithostratigraphical scheme. Units of higher order are supergroup, group and subgroup; the formation will be subdivided in member, key horizon resp. lithofacies unit and finally bed or layer. The elements "key horizon"- resp. "facies unit" are here informally used (advised by E. Nitsch, Freiburg, pers. comm.), e.g. to cover correlative continuities of erosion events (following the concept of "dual lithostratigraphy" by Lutz et al. 2005). Lithostratigraphical symbols follow the SEP 3 standards (Denino-Thiessen et al. 2002, LGRB 2011, E. Nitsch, pers. comm.). The formations refer to the four areas outlined above, i.e. to the various sedimentary environments and to sediment preservation.

- Central part of the Rhineglacier area, between Bodensee and Donau Valley: This is a primarily glacial environment, covered by three formations that also include fluvial and lacustrine deposits. Three major unconformities generate the boundaries of the formations, they refer to the three generations of overdeepened basins and, basically, the Bodensee amphitheatre as outlined above (Hasenweiler-Fm., Illmensee-Fm., Dietmanns-Fm.).

- Each formation is subdivided into members representing different combinations of glacial, fluvial and lacustrine sediments. Regarding different till assemblages, there are "glacial" members labelling different parts of till sequences:

- Succession with active ice sediments lying below sands and gravels of downmelting stagnant ice;

- drumlinized till featuring advancing ice, and its

- correlative downmelting sediments deposited as infill of glacial basins.

- Terminal moraine sediments marking the turning point from active to downmelting ice sediments are addressed as

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key horizons. Finally, there are fluvial sediments representing both, meltwater and non-glacial systems. They are often unspecific with regard to the glacial cyclicity and from there subsumed as "fluvial" member.

- Isolated glacial deposits: this formation comprises deposits that predate the Dietmanns-Fm. and further isolated deposits along the Hochrhein Valley.

- The pre-Dietmanns deposits are subsumed as members of the Steinental-Fm. Their common feature is that they are all embedded in or covering the landsurface of the 'Deckenschotter' landsystem, with no evidence of subglacial overdeepening.

- The glacial deposits along the Hochrhein Valley are subsumed as Haseltal-Fm. They are attributed to Middle Pleistocene ice advances of the Rhone Glacier (Valais Glacier) into the Hochrhein Valley.

- The nonglacial or periglacial fluvial environment is covered by three formations: the Oberschwaben-Deckenschotter-Fm., the Hochrhein-Deckenschotter-Fm., and the Rheingletscher-Terrassenschotter-Fm.

- The Oberschwaben-Deckenschotter-Fm. is subdivided in different members according to differing petrographical composition of the gravels. The 'Hochrhein-Deckenschotter' and the 'Rheingletscher-Terrassenschotter' are subdivided into members by means of terrace levels ('Höhere Hochrhein-Deckenschotter', 'Tiefere Hochrhein-Deckenschotter', 'Rheingletscher-Hochterrassenschotter', 'Rheingletscher-Niederterrassenschotter'). This goes along with different amounts of surface weathering (e.g. 'Hochterrasse' ~2 m, 'Niederterrasse' ~1 m).

- The southern URG acts as the "final" sediment trap for coarse alpine debris between Rhine and Rhone. Its succession has been subdivided in Neuenburg-Fm. and Breisgau-Fm.

- The Neuenburg-Fm. is reflected in the huge sediment fan located between the mouth of the Hochrhein Valley and the Kaiserstuhl volcanoe. The succession consists of two cycles of fluvial gravels, each including a coarse basal event horizon (key horizon) that is suggested to represent a correlative continuity of the erosion unconformities of the Bodensee area. This deposit is suggested to be input- i.e. climate-controlled.

- The composition of the gravel beds of the underlying Breisgau-Fm. ranges between well and poorly sorted. The diamictic beds include altered, weathered or even decomposed pebbles, often bearing evidence of palaeosol processes. With regard to the sediment thickness of up to 200 m, their preservation will primarily depend on subsidence.

To follow, some short definitions of the formations are introduced that are suggested to constitute a lithostratigraphy of the Quaternary of the southwest German Alpine Foreland, including sub-units as members, facies units (informally introduced) and key horizons. The full definitions will be published in the internet-based "Litholex" of the German Stratigraphic Commission (DSK 2011 ff.).

4.1 Hasenweiler-Formation

Hasenweiler-Fm. (qHW, Tab. 3, Fig. 5): unconformity-bounded lithostratigraphical unit, comprising all glacial, fluvial and lacustrine sediments deposited above the "Hasenweiler unconformity" (D1-unconformity). The sediments represent only one ice advance. Its active-ice- and downmelting sediments are deposited in two different locations (~ members, qHWT, qHWb). The outward boundary of the Hasenweiler-Fm. is marked by the terminal moraines of the 'Innere Jungendmoräne' (IJE, key horizon) that reflect the maximum of the ice advance.

- Sediment infill of overdeepened basins of the Hasenweiler-Fm. ('Hasenweiler Beckensedimente', qHWb-Mb). Lower boundary: D1-unconformity. The typical succession reflects downmelting ice, beginning with (1) coarse-grained diamicton, grading up into (2) matrix-rich diamicton (waterlain till) and ending up with (3) laminated and massive fines. The succession terminates with (4) postglacial clay-rich or organic fines. The succession may be disrupted by intervals of diamicton (slumps) or substituted by deltaic gravels, but there is no subglacial till (cf. qHWT). Sedimentation may still be ongoing, e.g. in the actual Bodensee Basin. Sediment thickness: average 50 m, maximum > 100 m.

- The Tettnang-Mb. (qHWT) refers to the till cover of the areas between the basins of the Hasenweiler-Fm. This is primarily a deformation till featuring active ice, its surface shows frequently (though not always) a drumlin relief. The till consists largely of cycles of diamicton that may be substituted by gravel-dominated sediment packages, often at the ice-up side of drumlin-landforms. Resulting from a "deformable bed", the unit displays the D1-unconformity. It is the most widespread glacial unit of the Rhineglacier area, reaching from the Bodensee to the IJE terminal moraine. Sediment thickness: average 10 m, maximum 30 m.

- Throughout the Hasenweiler-Fm., deposits of fluvial sands and gravels are subsumed as 'Hasenweiler Schotter' (qHWg). They are mainly in contact with the IJE, but there are also some locally scattered downmelting gravels in large interdrumlin depressions (Tettnang-Mb.), and the quite continuous gravel-infill along larger valleys that are usually eroded below the D1-unconformity (e.g. Argen, Wolfegger Ach).

Important sub-units of the members of the Hasenweiler-Fm. are:

- IJE terminal moraine (key horizon of the qHWT) marking the outward boundary of the qHW-Fm. i.e. the turning point from ice advance to downmelting. They

Tab. 3: Lithofacies units of the Hasenweiler-Formation.

Tab. 3: Lithostratigraphische Einheiten der Hasenweiler-Formation.

<table>
<tr><th>Chronostratigraphy</th><th>Formation</th><th colspan="2">Member</th><th>Key horizons</th></tr>
<tr><td>Holocene</td><td rowspan="2">Hasenweiler-Fm.
qHW</td><td rowspan="2">Hasenweiler-Beckensediment
qHWb</td><td></td><td></td></tr>
<tr><td rowspan="2">Innenwall-Würm</td><td rowspan="2">Tettnang-Till
qHWT</td><td rowspan="2">IJE</td></tr>
<tr><td colspan="2">D1-unconformity</td></tr>
</table>

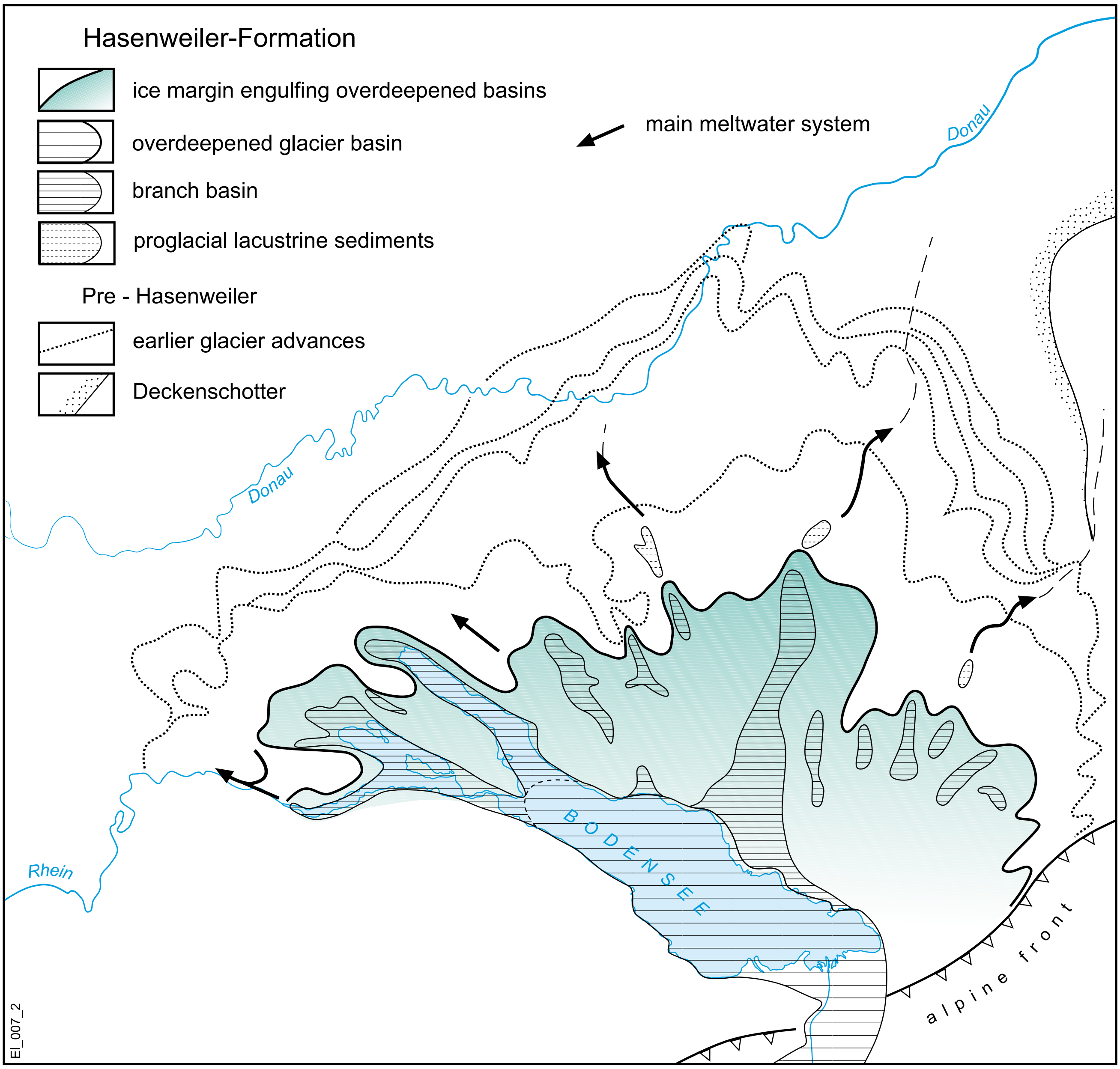

Fig. 5: Glacial basins and terminal moraines of the Hasenweiler-Formation. Although the branch basins are still radially orientated, this system is almost completely focussed towards the Rhine Valley i.e. to the west. This is also indicated by the NW elongation of the central Bodensee Basin ('Bodensee-Stammbecken'). – The highs between the branch basins are largely covered by drumlins (Tettnang-Mb.). Cf. Ellwanger *et al. 2011.*

Abb. 5: Glazialbecken und Endmoränen der Hasenweiler-Formation. Obwohl die Zweigbecken nach wie vor radial orientiert sind, ist Ihre Hauptausrichtung zum Rhein gerichtet, also nach Westen. Auch die Längserstreckung des zentralen Bodenseebeckens (Bodensee-Stammbecken) weist nach NW. – Die Hochgebiete zwischen den Zweigbecken sind weiträumig von Drumlins bedeckt (Tettnang-Subformation).

are inconspicuous landforms consisting of diamictons, gravels and sands from downmelting ice. Only few push moraines are yet known.
- Bodensee-Sediment (local "facies unit" of the qHWb).
- Eskers and related hills consisting of gravels deposited in ice-dammed channels, reflecting conspicuous landforms and sediment bodies (local "facies unit" of the qHWb).

4.2 Illmensee-Formation

Illmensee-Fm. (qIL, Tab. 4, Fig 6): unconformity-bounded lithostratigraphical unit, comprising all glacial, fluvial and lacustrine sediments deposited between "Illmensee unconformity" (D2-unconformity) and "Hasenweiler unconformity" (D1-unconformity). Its sediments comprise evidence of two ice advances. Regarding the first advance, active-ice- and downmelting sediments are again deposited in two different locations (~ members, qILD, qILb); the sediments of the last advance lie in stratigraphical succession (~ one member, qILK). There are two terminal moraine walls (key horizons): the 'Altmoränen-Innenwall' (last ice advance of the penultimate glaciation) marking the outward boundary of qIL, and the 'Äussere Jungendmoräne' (ÄJE), marking approximately the so-called "last glacial maximum" (LGM).

- Sediment infill of overdeepened basins of the Illmensee-Fm. (qILb-Mb., 'Illmensee Beckensedimente'). Lower boundary: D2-unconformity. The typical succession re-

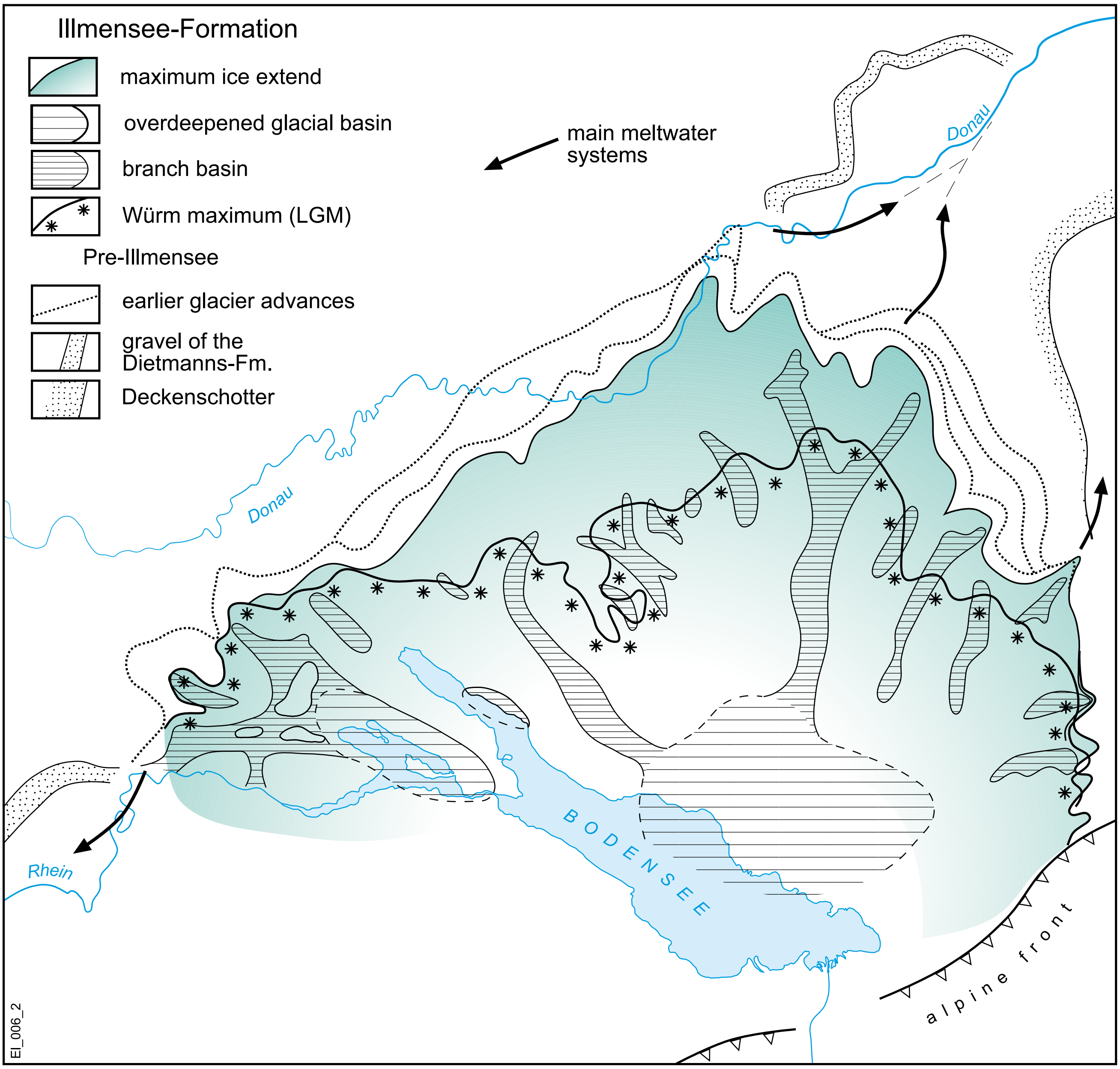

Fig. 6: Glacial basins and terminal moraines of the Illmensee-Formation. There are two central basins, one at the outlet of the overdeepened alpine Rhine Valley, the other in the westernmost part of the Bodensee area, leading over to the topography of the adjoining Swiss Midlands. The two central basins were probably parted by a Molasse high (its remnants are still present at the actual shore of the Bodensee). – Many of the branch basins of the Illmensee-Fm. are related to the valleys that go out from the LGM terminal moraine wall and where the 'Rheingletscher-Niederterrassenschotter' were deposited.

Abb. 6: Glazialbecken und Endmoränen der Illmensee-Formation. Es entstanden zwei Stammbecken, eines an der Talmündung des übertieften alpinen Rheintals, das andere im westlichen Bodenseegebiet, das zur Topographie des angrenzenden Schweizer Mittellandes überleitet. Die beiden Zentralbecken (Stammbecken) waren höchstwahrscheinlich durch ein Molasse-Hochgebiet voneinander getrennt, dessen Reste am Ufer des Bodensees noch heute vorhanden sind. – Viele Zweigbecken der Illmensee-Formation stehen in Verbindung mit den Tälern, die von der Äußeren Jungendmoräne ausgehen und in denen Niederterrassenschotter abegelagert wurden.

flects downmelting ice. It begins with (1) coarse-grained diamicton, grading up into (2) matrix-rich diamicton (waterlain till) and ends up with (3) laminated and massive fines. Again, coarser diamictic slumps or deltaic gravels may be included. Next unit to follow are sand to gravel with clay-rich or organic-rich fines (4) that may contain pollen reflecting the Eemian or early Würmian warm climate. Further up, proglacial fines (5) continuing qILb, or gravels (qIlg) or diamicton of the Kissleg-Mb. (qILK) may follow. Push moraines of the 'Äussere Jungendmoräne' (ÄJE), displaying the most conspicuous terminal moraine wall of the Alpine Foreland (key horizon), are frequently lobbing across the basins.

- The Dürmentingen-Mb. (qILD) refers to the sediment cover of elevated areas adjoining the basins of the Illmensee-Fm. outside of the ÄJE terminal moraine. Largely, this unit features again active ice, showing a moderately drumlinized surface, with cycles of deformed diamicton. Close to the margin of the correlative qILb basins, very coarse diamicton with large boulder-blocks (correlative to the D2-unconformity) may substitute the till. With increasing distance to the basins, downmelting sediments may become more frequent. They include sands and gravels and, within small interdrumlin basins, downmelting successions with fines and postglacial organic-rich sediments.

- The Kisslegg-Mb. (qILK) refers to the till sequence and correlative deposits that cover completely the area between IJE and ÄJE. Depending on the local topography it continues within the IJE underlying sediments of the Tettnang-Mb. Immediately outside of the ÄJE, it intercalates with qILg gravels. The succession begins with deformed and sheared diamicton (active-ice deposit) and continues with diamicton, sand, gravels and fines (downmelting deposits). Depending on the underlying relief, the land surface may be structured in a "kame and kettle" topography or in kames terraces.

- Throughout the Illmensee-Fm., deposits of fluvial sands and gravels are subsumed as qILg-Mb. They are most frequently outgoing from the ÄJE within the qILb-basins (correlative to the qRTN outside of the basins), but also locally consist of scattered downmelting deposits (large kames terraces, channel fill etc.).

Important sub-units of the members of the Illmensee-Fm. are:

- 'Altmoränen-Innenwall', the terminal moraine of the qILD ice advance (key horizon, qILDe), consisting of diamictons, gravels and sands, occasionally push moraines.
- 'Äußere Jungendmoräne' (ÄJE), the most conspicuous terminal moraine wall of the Alpine Foreland (key horizon, qILKe), frequently push moraines.
- Eskers and related hills consisting of gravels deposited in ice-dammed channels, reflecting conspicuous land forms and sediment bodies (local "facies unit" of the qILK).

4.3 Dietmanns-Formation

The Dietmanns-Fm. (qDM, Tab. 5, Fig. 7) is an unconformity-bounded lithostratigraphical unit, comprising all glacial, fluvial and lacustrine sediments deposited between the "Dietmanns unconformity" (D3-unconformity) and the "Illmensee unconformity" (D2-unconformity). Its sediments again show evidence of two ice advances. The first advance again comprises a till sequence (qDMV) and the infill of glacial basins (qDMb), the second just a till sequence (qDMS). There are two ice margins, both with terminal moraines that include push moraines (Fig. 7)

- Sediment infill of overdeepened basins of the Dietmanns-Fm. (qDMb-Mb., Dietmanns Beckensedimente). Lower boundary: D3-unconformaty. They represent the eldest of the yet known three generations of glacial basins. Some basins are quite deep, e.g. the Tannwald Basin at Schneidermartin almost 200 m. The typical succession reflects downmelting ice. It begins with coarse-grained diamicton, grading up into matrix-rich diamicton (waterlain till) and ends up with laminated and massive fines. Again, coarser diamictic slumps or deltaic gravels may be included. Next unit to follow are sand to gravel with clay-rich or organic-rich fines that may contain pollen reflecting the Holsteinian warm climate. The sediments to follow are mostly attributed to other members, e.g. till sequences beginning with the qDMS-Mb. On several occasions the relief of this generation of glacial basins was reversed by the overlying sediments (e.g. Waldburg-Basin).

- The Vilsingen-Mb. (qDMV) refers to the till cover of the elevated areas between the Dietmans basins and outside of the 'Altmoränen-Aussenwall'. The Vilsingen deposits are diamicton cycles that are often covered by several

Tab. 4: Lithofacies units of the Illmensee-Formation.

Tab. 4: Lithostratigraphische Einheiten der Illmensee-Formation.

<table>
<tr><th>Chronostratigraphy</th><th>Formation</th><th colspan="3">Member</th><th>Key horizons</th></tr>
<tr><td>Aussenwall-Würm</td><td rowspan="5">Illmensee-Fm.
qIL</td><td>Illmensee-Schotter
qILg</td><td colspan="2">Kisslegg-Mb.
qILK</td><td>ÄJE</td></tr>
<tr><td>Mittelwürm</td><td colspan="2" rowspan="4">Illmensee-Beckensediment
qILb</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Frühwürm</td></tr>
<tr><td>Eemian</td><td rowspan="3">Dürmentingen-Mb.
qILD</td><td></td></tr>
<tr><td rowspan="2">Innenwall-Riss</td><td rowspan="2">Altmoränen-Innenwall</td></tr>
<tr><td colspan="3">D2-unconformity</td></tr>
</table>

Tab. 5: Lithostratigraphische Einheiten der Dietmanns-Formation.

Tab. 5: Lithofacies units of the Dietmanns-Formation.

<table>
<tr><th>Chronostratigraphy</th><th>Formation</th><th colspan="3">Member</th><th>Key horizons</th></tr>
<tr><td>Aussenwall-Riss</td><td rowspan="4">Dietmanns-Fm.
qDM</td><td>Dietmanns-Schotter
qDMg</td><td colspan="2">Scholterhaus-Mb.
qDMS</td><td>Altmoränen-Außenwall</td></tr>
<tr><td>early Rissian</td><td colspan="2" rowspan="3">Dietmanns-Beckensediment
qDMb</td><td></td><td></td></tr>
<tr><td>Holsteinian</td><td rowspan="3">Vilsingen-Mb.
qDMV</td><td></td></tr>
<tr><td rowspan="2">Innenwall-Hosskirch</td><td rowspan="2">Pflummern-Till</td></tr>
<tr><td colspan="3">D3-unconformity</td></tr>
</table>

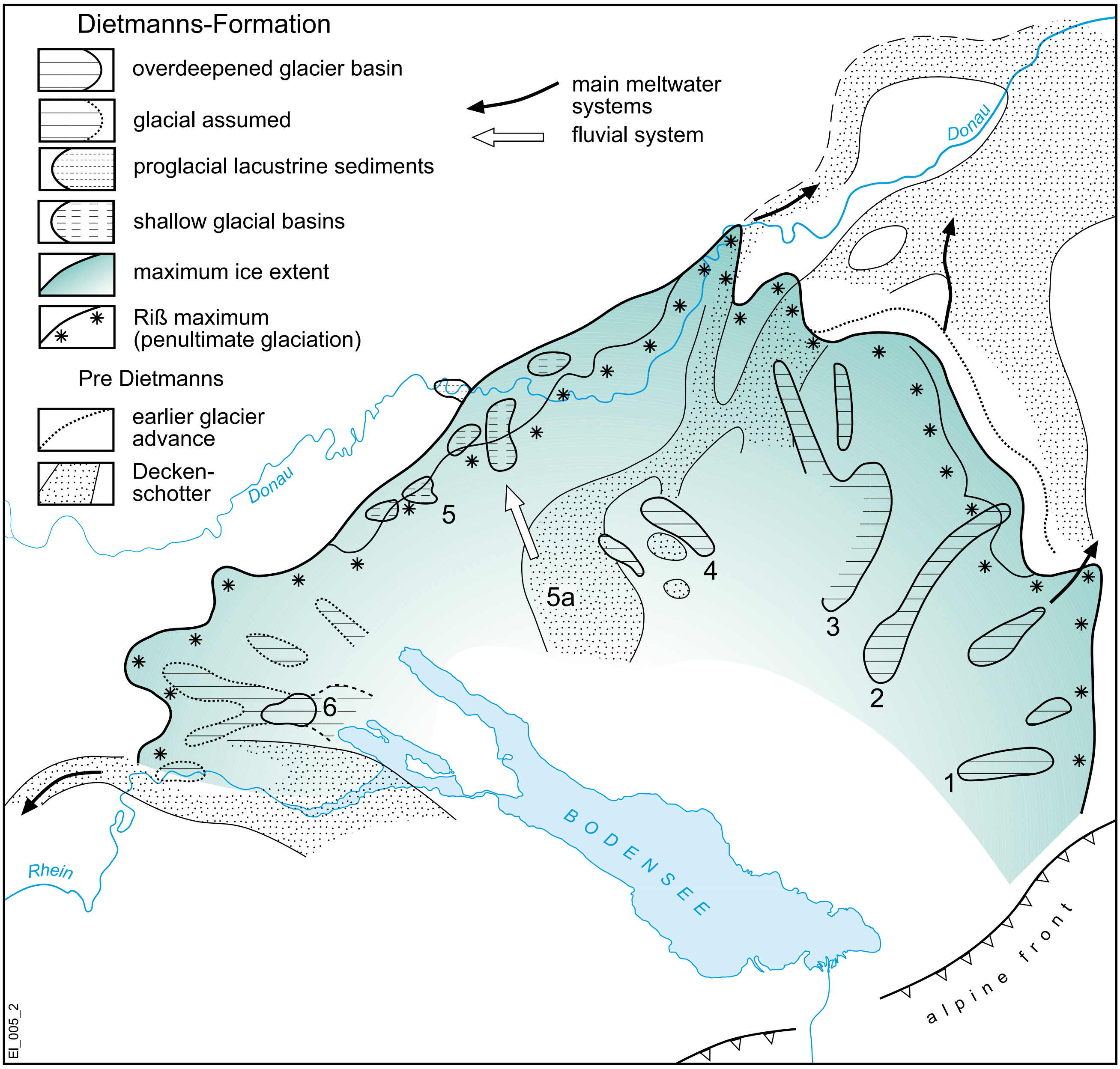

Fig. 7: Glacial basins and terminal moraines of the Dietmanns-Formation. It is suggested that this time slice marks the onset of overdeepening in the area. There are radial branch basins in the eastern part of the Rhineglacier area but no central basin alike to the present Bodensee Basin can be recognized. There are also no deep basins in the northwest, where the character of the "old" surface of a prealpine ramp still prevails. – The major branch basins are: 1 the Isny Basin (HGK 2010), 2 the Waldburg-Wurzach Basin (Fiebig 1995, 2003, Ellwanger 2003), 3 the Tannwald Basin (Ellwanger et al. 1995, Ellwanger 2003, Hahne 2010), and 4 the Hosskirch Basin (Ellwanger et al. 1995, Hahne 2010). 5, several shallow basins in the northwest follow the ice margin, including 5a delta deposits of the Holsteinian interglacial, serving as evidence for the up-river absence of deep basins (Bludau 1995, Müller 2001, Ellwanger, Fiebig & Heinz 1999, Ellwanger et al. 2011). 6 the Singen Basin (Szenkler & Bock 1999).

Abb. 7: Glazialbecken und Endmoränen der Dietmanns-Formation. In diesem Zeitabschnitt setzte die Übertiefung in der Region ein. Es gibt radial ausgerichtete Zweigbecken im östlichen Rheingletschergebiet, aber keine Hinweise auf ein zentrales Stammbecken, vergleichbar mit dem heutigen Bodenseebecken. Es gibt auch keine tiefen Becken im Nordwesten, dort blieb der Charakter der „alten" Rampen-artigen Landschaft mit außeralpinen Vorbergen erhalten. – Die großen Zweigbecken sind: 1 das Isny Becken (HGK 2010), 2 das Waldburg-Wurzach Becken (Fiebig 1995, 2003, Ellwanger 2003), 3 das Tannwald Becken (Ellwanger et al. 1995, Ellwanger 2003, Hahne 2010), und 4 das Hosskirch Becken (Ellwanger et al. 1995, Hahne 2010). 5, mehrere flache Becken entlang des Eisrands im Nordwesten. Darin enthalten sind Delta-Schüttungen (5a), in denen das Holstein Interglazial pollenstatigraphisch nachgewiesen ist. Diese Sedimente sind der Nachweis für das Fehlen von tiefen Becken weiter proximal (Bludau 1995, Müller 2001, Ellwanger et al. 1999, 2011). 6 das Singen Becken (Szenkler & Bock 1999).

meters of weathered periglacial sediments. They are rarely exposed.

- The Scholterhaus-Mb. (qDMS) refers to the till sequence and correlative deposits inside of the 'Altmoränen-Aussenwall'. The Biberach-Scholterhaus gravel pit is the classical exposure of this till in a succession of qDMg-gravels. The till sequence consists of deformed and sheared diamicton as active-ice deposit and diamicton, sand, gravels and fines as downmelting deposits.

- Throughout the Dietmanns-Fm., deposits of fluvial sands and gravels are subsumed as Dietmanns-Schotter (qDMg-Mb.). In the adjoining periglacial area they are correlated with the Rheingletscher-Hochterrassenschotter. In the central Rhineglacier area, several gravel-cycles are in stratigraphical succession. In the east and west Rhineglacier area these cycles correlate with two or more terrace levels (Iller Valley, Klettgau Valley).

Important sub-units of the members of the Dietmanns-Fm. are:

- 'Altmoränen-Aussenwall', the terminal moraine of the qDMS ice advance (key horizon, qDMSe), consisting of diamictons, gravels and sands, quite often as push moraines.
- Pflummern Till (qDMP), an isolated deposit of diamicton, sand and gravel located north of Riedlingen. It is suggested that it represents a sub-unit of the qDMV-Mb.

4.4 Isolated glacial deposits

Various isolated glacial deposits of the Rhineglacier area (Fig 8) and along the Hochrhein Valley are subsumed as Steinental-Fm. (Tab. 6) and Haseltal-Fm. (Tab. 7). The Steinental-Fm. subsumes pre-Dietmanns deposits of the Rhineglacier area, the Haseltal-Fm. refers to alpine deposits of the Rhone Glacier (Valais Glacier) along the Hochrhein Valley.

Steinental-Fm. (qST): lithostratigraphical unit comprising four isolated glacial deposits. There is no evidence that any of these deposits may be related to glacial overdeepening, so they are suggested to be part of the "fluvial" landsystem of the 'Deckenschotter'.

- The Steinhausen-Till (qSTH) refers to a diamicton that is suggested to represent the uppermost unit of glacial till in a small stripe outside the till of the Vilsingen-Mb. between Biberach and Aitrach ('Mindel' moraines sensu Schreiner & Ebel 1981). It is covered by several meters of weathered periglacial sediments and only poorly exposed. It has also been identified in several wells beneath the qDMV deposits (e.g. Schreiner 1982).

- The Unterpfauzenwald-Till (qSTU) refers to a glacial diamicton near Steinental ('Haslach' moraines sensu Schreiner & Ebel 1981). It represents the only yet known Early Pleistocene till sequence at the landsurface of the Rhineglacier area. (cf 2.3.2.1)

Tab. 7: Lithofacies units of the Haseltal-Formation.

Tabelle 7: Lithostratigraphische Einheiten der Haseltal-Formation.

Chronostratigraphy	Formation	Member	
Middle Pleistocene	Haseltal-Fm. qHT	Haseltal-Becken-sediment qHTb	Birndorf-Mb. qHTB

- The Lichtenegg-Till (qSTL) refers to a succession of diamicton, sand and gravel within 'Mindel-Deckenschotter' in the central part of the Rhineglacier area. A detailed description has been provided by Menzies & Ellwanger (2010). (cf 2.3.3.1)

- The Schrotzburg-Till (qSTS) refers to a succession of diamicton, sand and gravel that within the 'Tiefere Hochrhein-Deckenschotter' in the western part of the Rhineglacier area. A detailed description has been provided by Graf (2009).

The Haseltal-Fm. (qHS) is a lithostratigraphical unit comprising alpine glacial and lacustrine sediments along the Hochrhein Valley. It includes glacio-lacustrine and glacial sediments (qHSb, qHSB) related to different lobes of the Rhone Glacier (Valais Glacier) that overflew the Swiss Jura mountains towards the Black Forest.

- The unit Haseltal-Beckensediment (qHSb) refers to glaciolacustrine and gravitative deposits in overdeepened basins and ice dammed lakes of the Rhone Glacier.

- The Haseltal Basin is one of several glacial basins that are carved into crystalline and Permian rocks of the Black Forest. Lower boundary: D3-unconformity. The succession begins with diamicton reflecting downmelting ice, grading up into red and grey laminated and massive fines, and terminates with organic-rich fines that include pollen spectra of the Holsteinian (Hahne 2010). It includes packages of local debris (mainly Permian red sandstone).

- In the Klettgau Valley is another deposit of fine sediments of an ice-dammed lake overlying the gravels of the 'Rheingletscher-Hochterrassenschotter' (Verderber 1992, 2003).

- The Birndorf-Mb. (qHSB) subsumes deposits of alpine debris (diamicton, gravel, sand and fines) at the southern slopes of the Black Forest. They consist of isolated kames terraces, small ice-dammed lake deposits, but also till or debris covering parts of the slopes. Their preservation depends on the local topography.

4.5 The pre- and periglacial fluvial environment

The Quaternary of the fluvial environment of large valleys in the southwest German Alpine Foreland (Tab. 8) is referred to in three formations: The 'Oberschwaben-Deckenschotter' (qpDO) covering the 'Deckenschotter' remnants in the area between Bodensee and Donau Valley, the 'Hochrhein-Deckenschotter' (qpHD) covering the western Bodensee and Hochrhein areas, and the 'Rheingletscher-Terrassenschotter' (qRT) covering gravels of the 'Hoch'- and 'Niederterrasse' in both areas. They all consist of coarse fluvial gravels.

Tab. 6: Lithofacies units of the Steinental-Formation.

Tab. 6: Lithostratigraphische Einheiten der Steinental-Formation.

Chronostratigraphy	Formation	Member			
Middle Pleistocene (OIS12?)	Steinental-Fm. qST	Steinhausen-Till qSTH			
Early Pleistocene (Calabrian)			Unterpfauzenwald-Till qSTU	Lichtenegg-Till qSTL	Schrotzburg-Till qSTS

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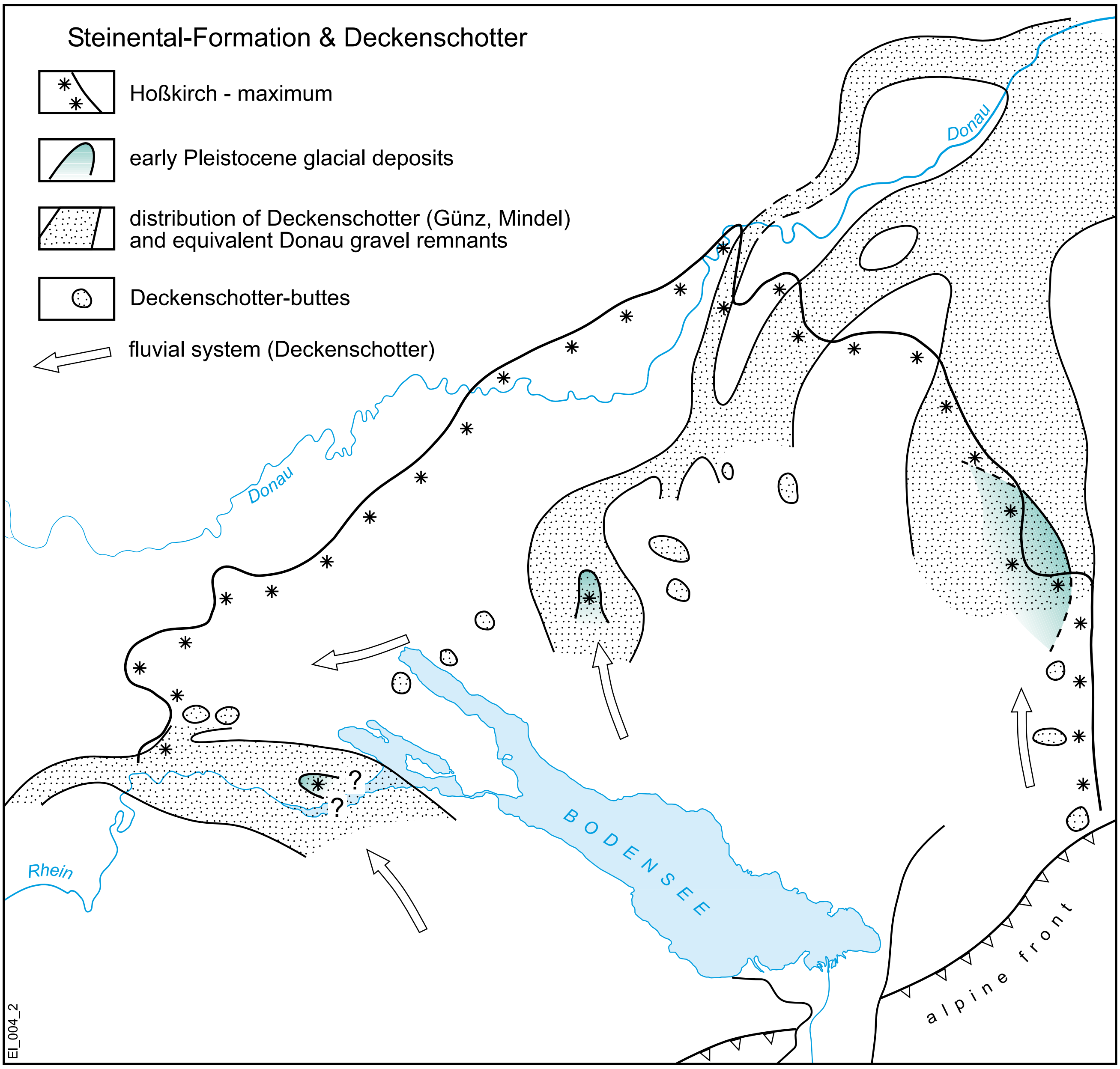

Fig. 8: 'Deckenschotter', till and terminal moraines of the Steinental-Formation. No indication for glacial overdeepening is known. The till deposits are believed to be the remnants of valley-glaciers.

Fig. 8: Deckenschotter, Till und Endmoränen der Steinental-Formation. Sie sind die ältesten eiszeitlichen Relikte und deuten auf eine nur geringe glaziale Umformung der voreiszeitlichen Landschaft hin.

The 'Oberschwaben-Deckenschotter' (qpDO) Formation consists of three members featuring different petrographical composition:

- 'Donau-Deckenschotter' (qpODD), poor in crystalline (< 5 %) but rich in Dolomite, probably reflecting a source area still east of the actual valley of the alpine Rhine.
- 'Günz-Deckenschotter' (qpODG), poor in crystalline but rich in limestone from nappes that are located close to the alpine margin. This composition is suggested to reflect the beginning of the incision of the alpine Rhine Valley.
- 'Mindel-Deckenschotter' (qpODM), rich in crystalline (10–30 %). The composition of the gravels now reflects the modern course of the alpine Rhine, but before the valley became glacially overdeepened. The inner-alpine catchment area of the Rhine is now sufficiently large to enable ice advances even into the Alpine Foreland (e.g. members of the qST-Fm.).

'Hochrhein-Deckenschotter' (qpHD): This unit is two-parted by means of terrace stratigraphy. Both subunits, the 'Höhere-Hochrhein-Deckenschotter' (qpHDh) and the 'Tiefere-Hochrhein-Deckenschotter' (qpHDt), consist of up to three accumulation cycles in stratigraphical succession (Verderber 1992, 2003, Graf 1993, 2009). There are again differences in petrographical composition, but they refer primarily to the different Swiss alpine valleys (Limmat, Reuss, Aare, Rhone). – Although the thickness of the 'Deckenschotter' along the Hochrhein Valley amounts up to several tens of meters, a much larger sediment volume has been transported through the valley into the southern URG (Breisgau-Fm.). I.e. the valley erosion and 'Deckenschotter' deposition depend largely on base level variations in the URG that are probably primarily controlled by tectonics (Ellwanger 2003).

'Rheingletscher-Terrassenschotter' (qRT): This unit subsumes two members: the 'Rheingletscher-Hochterrassenschotter' (qRTH) and the 'Rheingletscher-Niederterrassenschotter' (qRTN). Again, both subunits locally consist of two or more accumulation cycles in stratigraphical succession that may, elsewhere, correspond with different terrace levels. – The 'Terrassenschotter' are traditionally suggested to be meltwater deposits, correlative with sub- and proglacial gravels (Dietmanns- and Illmensee-gravels) and with no direct connection to the alpine sediment source area because the lake basins at the alpine margin lie in between. In this scenario, the sediment input terminates abruptly when the ice melts down, and only eventually restarts after the basins are again filled up with sediments. Preliminary results from luminescence dating indicate that this sediment input could have restarted at about 70 ka ("maximum" ages taken from Frechen et al. 2010 but doubted by Kock et al. 2009. Both papers also suggest different geological interpretations). – Again a much larger sediment volume has been transported through the valley into the URG (Neuenburg-Fm.).

4.6 The Upper Rhine Graben, southern part.

All alpine sediments that are deposited in the URG (Tab. 9) were beforehand transported through the Hochrhein Valley. In the southern URG, coarse gravels, pebbles and even blocks are deposited that are often coarser than gravels of the valley terraces. The coarse event layers were suggested

Tab. 8: Lithofacies units of the pre- and periglacial fluvial environment in the southwest German Alpine Foreland.

Tab. 8: Lithostratigraphische Einheiten der Prä- und Periglazial-Gebiete des Südwestdeutschen Alpenvorlands.

Chronostratigraphy	Formation	Member	Key horizon (e.g.)
Holocene	Rheingletscher-Terrassenschotter qRT	Rheingletscher-Niederterrassenschotter qRTN	Talauenschotter
Late Pleistocene			Niederterrassenschotter
Middle Pleistocene			Äpfingen Schotter
		Rheingletscher-Hochterrassenschotter qRTH	Baltringen Hochterrasse
			Ältere Hochterrasse
early Middle Pleistocene			
Early Pleistocene (Calabrian)	Oberschwaben-Deckenschotter qpOD	Mindel-Deckenschotter qpODM	
		Günz-Deckenschotter qpODG	
Early Pleistocene (Gelasian)		Donau-Deckenschotter qpODD	
Early Pleistocene (Calabrian)	Hochrhein-Deckenschotter qpHD	Tiefere Hochrhein-Deckenschotter qpHDt	
Early Pleistocene (Gelasian)		Höhere Hochrhein-Deckenschotter qpHDh	

Tab. 9: Lithofacies units of the southern Upper Rhine Graben.

Tab. 9: Lithostratigraphische Einheiten des südlichen Oberrheingrabens.

Chrono-stratigraphy	Formation	Member		Key horizons
Late Pleistocene	Neuenburg-Fm. qNE	Hartheim-Mb. qNEo	Zarten-Mb. qNEZ	Eventlayer
Middle Pleistocene		Nambsheim-Mb. qNEu		Eventlayer
Middle Pleistocene	Breisgau-Fm. qBR	Balgau-Mb. qBRo	Wasser-Mb. qBRW	Riegel-Horizont qBRR
Pliocene to Early Pleistocene		Weinstetten-Mb. qBRu		Hergheim-Schichten qBRH
	Iffezheim-Fm. qIF			

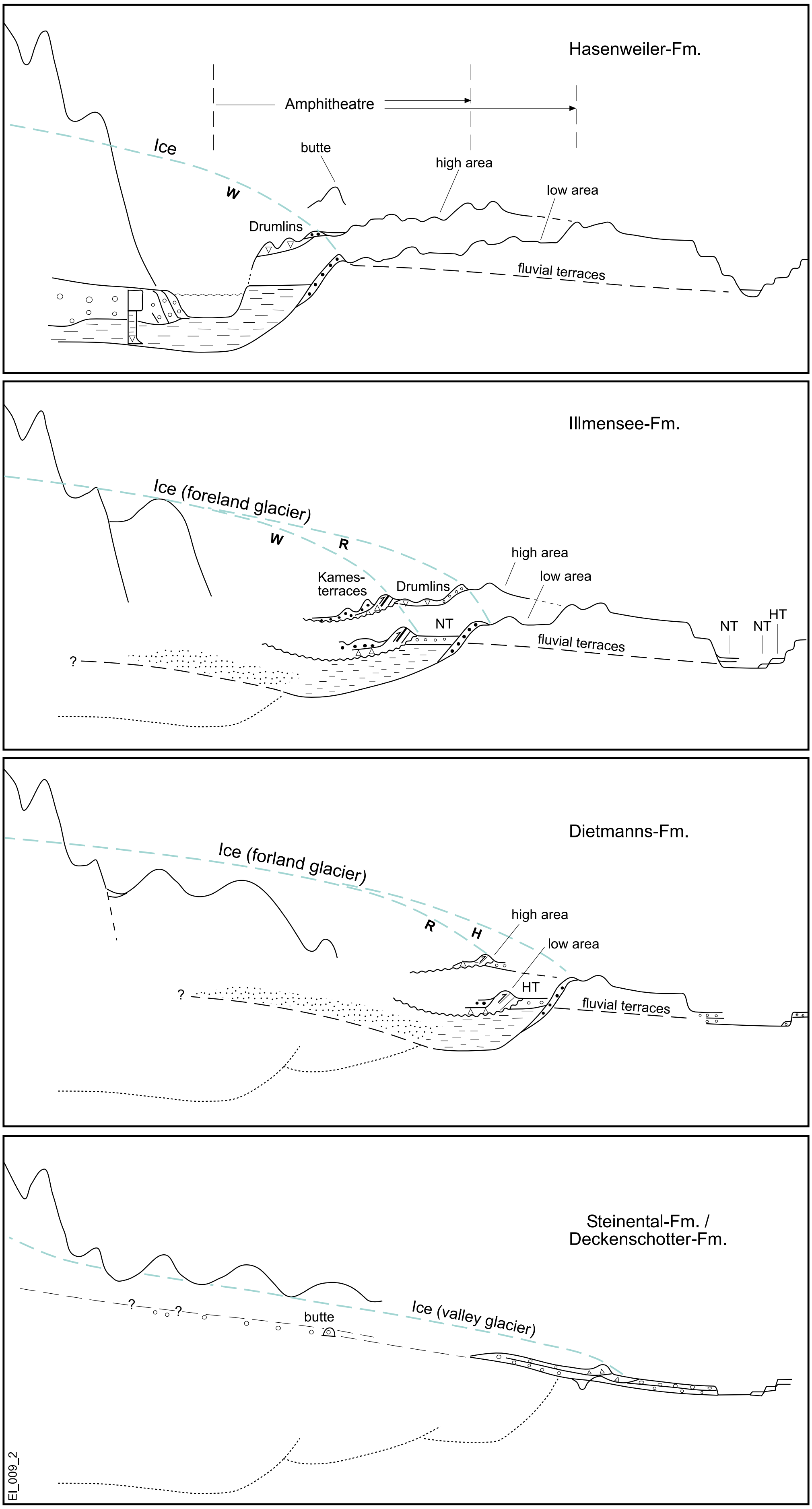

Fig. 9: Cartoon illustrating four steps of Pleistocene surface evolution of the Bodensee area, from a kind of ramp-topography to the present amphitheatre. Cf. ELLWANGER *et al. 2011.*

Fig. 9: Schrittweise Entwicklung der Landschaft im Pleistozän von einer Art Rampe hin zum heutigen Amphitheater (vgl. ELLWANGER *et al. 2011).*

to be correlative to morphogenetic reshaping of the valley and to the subglacial basin erosion at the alpine margin (Ellwanger 2003). The alpine input in the southern URG is referred to in two formations, the Breisgau-Fm. (qBR) and the Neuenburg-Fm. (qNE); they are further subdivided into members. The underlying Iffezheim-Fm. (qIF) is of local, non-alpine provenance. The boundary between qIF and qBR is diachronic, that is why both units begin in the Pliocene and go far up into the Pleistocene, in spite of their stratigraphical superposition.

The Breisgau-Fm. largely consists of graded alpine and local gravels. Esp. the local gravels are often altered, weathered or even completely disintegrated, indicating low sedimentation rates and possibly gravitative redeposition. Its thickness varies strongly, depending on the varying depth of the lower boundary that is primarily a matter of tectonical subsidence, supported by compaction of underlying fines. – This unit is suggested to be correlative to the 'Deckenschotter'.

The Neuenburg-Fm. (qNE) is reflected by the huge sediment fan located between the mouth of the Hochrhein Valley and the Kaiserstuhl volcanoe. The succession consists of two cycles of coarse fluvial gravels (Hartheim-Mb., qNEo, and Nambsheim-Mb., qNEu), each including a coarse basal event horizon (diamictic with pebbles and blocks). The sediment is usually unweathered. Its thickness averages between 30 m and 50 m; a large part of this is owed to the fan surface, some to compaction. – This unit is suggested to represent a correlative continuity of the erosion unconformities of the Bodensee area; it is input- i.e. climate-controlled.

According to sediment petrographical composition and heavy minerals, the sediment source of the lower and middle part of the Breisgau-Fm. are the Swiss Alps, that of the uppermost Breisgau-Fm. and the Neuenburg-Fm. is the Rhineglacier area (Hagedorn 2004).

5 Summary of relief evolution & discussion

Both, the chronostratigraphy and the lithostratigraphy of the Bodensee area that are presented here are suitable tools to describe the evolution of landforms and sediments during the Quaternary. However, the transformation of the topography from pre-alpine highlands into the actual amphitheatre landsystem with its overdeepened lake basins is better matched using the lithostratigraphical approach.

We distinguish seven steps (Figs. 3, 5, 6, 7, 8, cartoon Fig. 9):

1. The earliest Quaternary landsurface represents foothills and prealpine highlands acting as watershed between the 'Donau-Deckenschotter' of the Donau system in the east (Schädel 1950, Doppler 2003), and the eldest 'Hochrhein-Deckenschotter' of the Rhine system in the west (Schreiner 1992, Verderber 1992, 2003, Graf 1993, 2009). – Chronostratigraphy: According to Ellwanger, Fejfar & von Koenigswald, 1994 and Bolliger et al. 1996, both deposits represent the Gelasian stage.

2. The first 'Deckenschotter' remnants related to the actual Rhine Valley at the alpine margin are known as 'Günz-Deckenschotter'. They are incised below the level of the 'Donau-Deckenschotter'. Their petrographical composition reflects Helvetic and Ultrahelvetic nappes i.e. indicates the onset of erosion of the alpine Rhine Valley. This catchment area would be too small to enable an ice advance into the Alpine Foreland. – Chronostratigraphy: Early Pleistocene, according to Fromm (1989) and Rolf (1992).

3. The 'Mindel-Deckenschotter' are often (not always) incised below the 'Günz' level. Their petrographical spectra include crystalline pebbles from the central Alps, already reflecting the actual alpine Rhine Valley. This catchment area is large enough to enable ice advances into the Alpine Foreland. – Chronostratigraphy: Early Pleistocene, according to Fromm (1989) and Rolf (1992).

4. The eldest till deposits of the Rhineglacier area (subsumed in the Steinental-Fm.) show no evidence for glacial overdeepening. They are the Lichtenegg-Till, the Schrotzburg-Till, the Unterpfauzenwald-Till and the Steinhausen-Till (first advance of the Hosskirchian glacial stage. – Chronostratigraphy: Lichtenegg-Till, Early Pleistocene (Fromm 1989, Rolf 1992); Unterpfauzenwald-Till, grading into Bavelian peat (Hahne 2010); Steinhausen-Till, Hosskirchian stage (Hahne 2010).

5. The first deep basin erosion is related to the Dietmanns-Fm. There are radial branch basins in the eastern part of the Rhineglacier area but no central basin can be recognized. In the northwest, the character of the "old" surface of a prealpine ramp still prevails. Ice advance and meltwater discharge are still largely directed to the Donau Valley. – Chronostratigraphy: Hosskirchian to Rissian stage.

6. The deep basin erosion continues in the Illmensee-Formation. Now there are two central basins, one at the outlet of the overdeepened alpine Rhine Valley, the other in the westernmost part of the Bodensee area. Ice advance and meltwater discharge are now partly directed to the Donau Valley, partly to the Hochrhein Valley. – Chronostratigraphy: Rissian to Würmian stage.

7. The deep basin erosion of the Hasenweiler-Formation results in the NW elongated central Bodensee Basin ('Bodensee-Stammbecken'). Its branch basins are still radially orientated, but the system is now almost completely focussed towards the Rhine Valley i.e. to the west. – Chronostratigraphy: Würmian stage to Holocene.

The amount of Quaternary erosion since the 'Donau-Deckenschotter' seems larger in the Bodensee area than in both neighbouring areas, both downward and laterally (1 km resp. 70 km). This may be related to the reorientation of the system from the Donau to the Rhine, a setting that is unique in the Alpine Foreland. The erosion/sedimentation pattern of an eventual future ice advance is of course a matter of speculation, but most likely it will be the first Rhineglacier advance to be focussed towards the Hochrhein Valley alone. In this case, a new "most extensive" ice margin may result.

Lithostratigraphy proved to be very useful to understand and describe the morphodynamics of the Rhineglacier and to correlate with the close-by depocentres for resediments. This is due to the high spatial resolution in the Bodensee area. However, at least up to now, it does not match the difficulties of a supra-regional correlation, partly because of the insufficient knowledge on the sequence stratigraphical conditions in other glacial areas. To meet this obstacle, the chronostratigraphic approach seems more suitable.

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References

Bibus, E. & Kösel, M. (1996): Paläopedologische Klimazeugen zur Untergliederung des Rißeiszeiten-Komplexes im Rheingletschergebiet. – Eiszeitalter und Gegenwart, 46: 65–90; Hannover.

Bibus, E. & Kösel, M. (2003): Rezente und fossile Böden als Gliederungskriterium der Rheingletscherablagerungen am Höchsten. – Zeitschrift der Deutschen Geologischen Gesellschaft. 154: 343–356; Stuttgart.

Bibus, E., Bludau, W., Ellwanger, D., Fromm, K., Kösel, M. & Schreiner, A. (1996): On Pre-Würm glacial and interglacial deposits of the Rhine Glacier (South German Alpine Foreland, Upper Swabia, Baden-Württemberg). – In: Turner, Ch. (ed.): The early Middle Pleistocene in Europe: 195–204, Rotterdam (Balkema).

Bolliger, T., Fejfar, O., Graf, H. R. & Kälin, D. (1996): Vorläufige Mitteilung über Funde von pliozänen Kleinsäugern aus den höheren Deckenschottern des Irchels (Kt. Zürich). – Eclogae geologicae Helvetiae, 89, 3: 1043–1048; Basel.

Cohen, K.M. & Gibbard P.L. (2010): Global chronostratigraphy correlation table for the last 2.7 million years v. 2010. – IUGS International Commission on Stratigraphy's (ICS) Subcommission on Quaternary Stratigraphy (SQS). – Internet-Publ.: http://www.quaternary.stratigraphy.org.uk/charts/

Dehnert, A., Preusser, F., Kramers, J. D., Akçar, N., Kubik, P. W., R. Reber & Schlüchter, Ch. (2010): A multi-dating approach applied to proglacial sediments attributed to the Most Extensive Glacia-tion of the Swiss Alps. – Boreas, 39: 620–632. DOI: 10.1111/j.1502-3885.2010.00146.x.

Denino-Thiessen, D., Dominik, M., Haertlé, T., Hoffers, B., Hofmann, M. & Preuss, H. (2002): Anleitung zur Erfassung von Bohrungs- und Schichtdaten mit SEP 3. – Tagbuch-Nr. 32690/02, Niedersächsisches Landesamt für Bodenforschung, Fachinformationssysteme Angewandte Geologie, 39 S., NLfB (Hannover). – Internet-Publ.: http://www.gdfb.de/pdf/C39468303_L20.pdf

Doppler, G. (2003): Zur Gliederung von Ältesten Periglazialschottern und Älteren Deckenschottern im Rot-Günz-Gebiet (Oberschwaben und Bayerisch Schwaben). – Zeitschrift der Deutschen Geologischen Gesellschaft, 154, 2/3: 255–286; Stuttgart.

Doppler, G. & Jerz, H. (1995): Untersuchungen im Alt- und Ältestpleistozän des bayerischen Alpenvorlands – Geologische Grundlagen und stratigraphische Ergebnisse. – Geologica Bavarica, 99: 7–35; München.

Doppler, G, Kroemer, E., Rögner, K., Wallner, J., Jerz, H. & Grottenthaler, W.: Stratigraphic Classification of the Quaternary in Southern Bavaria. – Eiszeitalter und Gegenwart / Quaternary Science Journal, 60/2: 122–158; Hannover.

DSK (2011 ff.): LithoLex, Lithostratigraphisches Lexikon Deutschland im Internet. – Deutsche Stratigraphische Kommission. – Internet Publikation: http://www.bgr.bund.de/litholex

Eberl, B. (1930): Die Eiszeitenfolge im nördlichen Alpenvorland. – 427 S.; Augsburg (Vilser).

Ellwanger, D. (2003), unter Mitarbeit von Neeb, I. & Lämmermann-Barthel, J.: Eine landschaftsübergreifende Lockergesteinsgliederung vom Alpenrand zum Oberrhein. – In: Schirmer, W. (ed.): Landschaftsgeschichte im europäischen Rheinland. – GeoArchaeoRhein, 4: 81–124; Münster.

Ellwanger, D., Bibus, E., Bludau, W., Kösel, M. & Merkt, J. (1995): Baden-Württemberg. – In: Benda, L. (ed.): Das Quartär Deutschlands: 255–295; Berlin, Stuttgart, New York.

Ellwanger, D., Fejfar, O. & Koenigswald, W. von (1994): Die biostratigraphische Aussage der Arvicolidenfauna vom Uhlenberg bei Dinkelscherben und ihre morpho- und lithostratigraphischen Konsequenzen. – Münchner Geowissenschaftliche Abhandlungen, A 26: 173–191; München.

Ellwanger, D., Fiebig, M, & Heinz, J. mit Beiträgen zur Pollenanalyse von Bludau, W. (1999): Quartärgeologie des mittleren Rheingletschergebietes (Bittelschiess, Höchsten, Hoßkirch, Ostrach). – Jahresberichte und Mitteilungen des oberrheinischen Geologischen Vereins, N.F., 81: 217–230; Stuttgart.

Ellwanger, D, Simon, T. & Ufrecht, W. (2009): Die Lockersedimentfüllung des Blautals: Ergebnisse der neuen Forschungs-Kernbohrung am Kindergarten in Blaubeuren. – Laichinger Höhlenfreund, 44: 157–176, Laichingen

Ellwanger, D., Kimmig, B., Simon, T. & Wielandt-Schuster, U. (2011): Quartärgeologie des Rheingletschergebiets, Exkursion I. (29.04.2011). – Jahresberichte und Mitteilungen des oberrheinischen Geologischen Vereins, N.F., 93: 115–217; Stuttgart.

Fiebig, M. (1995): Pleistozäne Ablagerungen im süddeutschen und im neuseeländischen Alpenvorland – ein Vergleich). – Inaugural Dissertation Universität Freiburg: 122 S.; Freiburg.

Fiebig, M. (2003): Lithofazielle Untersuchungen an pleistozänen Sedimenten im östlichen Rheingletschergebiet. – Zeitschrift der deutschen Geologischen Gesellschaft, 154, 2/3: 301–342; Stuttgart.

Fiebig, M., Ellwanger, D., & Doppler, G. (in print): Pleistocene Glaciations of Southern Germany. – In: Ehlers, J, Gibbard, P.L. & Hughes, P.D. (eds.): Glaciations-Extent and Chronology. A closer look. Chapter 14; Amsterdam (Elsevier).

Frechen, M., E. A. Oches, & K. E. Kohfeld (2003): Loess in Europe – mass accumulation rates during the Last Glacial Period, Quaternary Science Reviews, 22: 1835–1857; Amsterdam.

Frechen, M., Ellwanger, D., Hinderer, M., Lämmermann-Barthel, J., Neeb, I. & Techmer, A. (2010): Late Pleistocene fluvial dynamics in the Hochrhein Valley and in the Upper Rhine Graben: chronological frame. – International Journal of Earth Sciences, 99, 8: 1955–1974. DOI: 10.1007/s00531-009-0482-9

Frenzel, B. (1991): Über einen frühen letzteiszeitlichen Vorstoß des Rheingletschers in das deutsche Alpenvorland. – In: Frenzel, B. (Hrsg.): Paläoklimaforschung, 1, Klimageschichtliche Probleme der letzten 130000 Jahre: 377–400; Stuttgart (Fischer).

Frenzel, B. & Bludau, W. (1987): On the duration of the interglacial to glacial transition at the end of the Eemian interglacial (deep sea stage 5e): Botanical and sedimentological evidence. – In: Berger, W. H. & Labeyrie, L. D. (eds.): Abrupt climatic changes – Evidence and implications. – NATO ASI, Series C: Mathematics and Physical Sciences, 216: 151–162; Dordrecht (Reidel).

Fromm, K. (1989): Paläomagnetische Altersbestimmungen an eiszeitlichen Quartärablagerungen bei Heiligenberg (Oberschwaben). – Niedersächsisches Landesamt für Bodenforschung – Geowissenschaftliche Gemeinschaftsaufgaben, Bericht Ar.-Nr. 105863, 19 S.; Hannover.

Gabriel, G., Ellwanger, D., Hoselmann, Ch., & Weidenfeller, M. (2008): The Heidelberg Basin Drilling Project. – Eiszeitalter und Gegenwart, Quaternary Science Journal 57, 3/4: 432 S.; Hannover.

Geotop Wyhlen (2007), http://www.geologie-des-dinkelbergs.de/geotourismus.html)

GLA (1995): Symbolschlüssel Geologie (Teil 1) und Bodenkunde Baden-Württemberg. – Geol. Landesamt Baden-Württ., Informationen, 5: 68 S. Freiburg i. Br.

Göttlich, K. (1974): Vorrißzeitliche Interglazialvorkommen in der Altmoräne des östlichen Rheingletschergebiets. – Geologisches Jahrbuch, A 18: 49–79; Hannover.

Graf, H.R. (1993): Die Deckenschotter der zentralen Nordschweiz. – Dissertation ETH Zürich – 151 S.; Zürich.

Graf, H.R. (2009): Stratigraphie und Morphogenese von frühpleistozänen Ablagerungen zwischen Bodensee und Klettgau. – Eiszeitalter und Gegenwart / Quaternary Science Journal, 58/1: 12–53; Hannover.

Graul, H. (1962): Eine Revision der pleistozänen Stratigraphie des schwäbischen Alpenvorlandes (mit einem bodenkundlichen Beitrag von K. Brunnacker). – Petermanns geographische Mitteilungen, 1962, 4: 253–271; Gotha.

Grüger, E. (1983): Untersuchungen zur Gliederung und Vegetationsgeschichte des Mittelpleistozäns am Samerberg in Oberbayern. – Geologica Bavarica, 84: 21–40; München.

Grüger, E. (1995): Pollenanalytische Untersuchungen an Sedimenten des Schmiecher Sees. – In: German et al. (1995): Die Entstehung des Schmiecher Sees aufgrund der Bohrung „Schmiecher See 1“. – Beihefte zu den Veröffentlichungen für Naturschutz und Landschaftspflege in Baden-Württemberg, Landesanstalt für Umweltschutz Baden-Württemberg,, 78, 74–83; Karlsruhe.

Grüger, E. & Schreiner, A. (1993): Riss-Würm und würmzeitliche Ablagerungen im Wurzacher Becken (Rheingletschergebiet). – Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 189: 81–117; Stuttgart.

Habbe, K.H. (1994): Das deutsche Alpenvorland. – In: Liedtke, H. & Marcinek, J. (Hrsg.): Physische Geographie Deutschlands: 439–475; Gotha (Perthes).

Habbe, K.A. (2003): Gliederung und Dauer des Pleistozäns im Alpenvorland, in Nordwesteuropa und im marinen Bereich – Bemerkungen zu einigen neueren Korrelierungsversuchen. – Zeitschrift der deutschen Geologischen Gesellschaft, 154, 2/3: 171–192; Stuttgart.

Habbe, K.H. (2007), unter Mitarbeit von Ellwanger, D. & Becker-Haumann, R.: Stratigraphische Begriffe für das Quartär des süddeutschen Alpenvorlandes. – Eiszeitalter und Gegenwart / Quaternary Science Journal, 56, 1/2: 66–83; Hannover.

Hagedorn, E.-M. (2004): Sedimentpetrographie und Lithofazies der jungtertiären und quartären Sedimente im Oberrheingebiet. – Dissertation Universität zu Köln, – 248 S., Köln (Internet-Publ. – http://kups.ub.unikoeln.de/volltexte/2004/1253/)

Hahne, J. (2010): Kommentare zu Pollendiagrammen von W. Bludau. – Interner Bericht, Az. 4762//10_2414, Landesamt für Geologie, Rohstoffe und Bergbau im Regierungspräsidium Freiburg; Freiburg.

HGK (2010): Hydrogeologische Karte Baden-Württemberg, Argen-Aach-Rinne Isnyer Becken. – 142 S.; Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg / Regierungspräsidium Freiburg – Landesamt für Geologie, Rohstoffe und Bergbau; Karlsruhe/Freiburg.

Häuselmann, Ph., Fiebig, M., Kubik, P.W. & Adrian, H. (2007): A first attempt to date the original ‘Deckenschotter’ of Penck & Brückner with cosmogenic nuclides. – Quaternary International, 164–165, 33–42. DOI: 10.1016/jh.quaint.2006.12.013

Klasen, N. (2008): Lumineszenzdatierung glazifluvialer Sedimente im nördlichen Alpenvorland. – Dissertation Universität zu Köln, – 209 + VIII S., Köln (Internet-Publ. – http://kups.ub.uni-koeln.de/volltexte/2008/2293/)

Kock, S., Huggenberger, P., Preusser, F., Rentzel R., & Wetzel, A. (2009): Formation and evolution of the Lower Terrace of the Rhine River in the area of Basel. – Swiss Journal of Geoscience, 102, 2: 307–321, DOI: 10.1007/s00015-009-1325-1

LGRB (2005): Symbolschlüssel Geologie Baden-Württemberg, Verzeichnis geologischer Einheiten; Freiburg. – Internet-Publ.: http://www.lgrb.uni-freiburg.de

LGRB (2011): Symbolschlüssel Geologie Baden-Württemberg. Verzeichnis geologischer Einheiten; Freiburg. – Internet-Publ.: http://www.lgrb.uni-freiburg.de

Litt, T., Ellwanger, D., Villinger, E. & Wansa, S. (2005): Das Quartär in der Stratigraphischen Tabelle von Deutschland 2002. – Newsletters on Stratigraphy, 41: 385–399; Stuttgart.

Litt, T. (2007): Das Quartär als chronostratigraphische Einheit. – Eiszeitalter und Gegenwart / Quaternary Science Journal, 56, 1/2: 3–6; Hannover.

Löscher, M. (1976): Die präwürmzeitlichen Schotterablagerungen in der nördlichen Iller-Lech-Platte. – Heidelberger Geographische Arbeiten, 45: 157 S.; Heidelberg.

Lutz, M., Etzold, A., Käding, K,. Lepper, J., Hagdorn, H., Nitsch, E. & Menning, M. (2005): Lithofazies und Leitflächen: Grundlagen einer dualen lithostratigraphischen Gliederung. – Newsletters in Stratigraphy, 41, 1–3: 211–223, Berlin – Stuttgart.

Menzies, J. & Ellwanger, D. (2004): Micromorphological Analysis of Complex Till Stratigraphy near Lichtenegg, Höchsten, Baden-Württemberg, Germany. – Deuqua Abstracts; Nijmegen.

Menzies, J. & Ellwanger, D. (2010): Insights into subglacial processes inferred from the micromorphological analyses of complex diamicton stratigrahy near Illmensee-Lichtenegg, Höchsten, Germany. – Boreas, 10.1111/j.1502-3885.2010.00194.x. ISSN 0300-9483.

Müller, U.C. (2000): A Late Pleistocene pollen sequence from the Jammertal, SW-Germany with particular reference to location and altitude as factors determining Eemian forest composition. – Vegetation History and Archaeobotany, 9, 2: 125–131.

Müller, U. (2001): Die Vegetations- und Klimaentwicklung im jüngeren Quartär anhand ausgewählter Profile aus dem südwestdeutschen Alpenvorland. – Tübinger Geowissenschaftliche Arbeiten, Reihe D, 07, 118 S.; Tübingen.

Neeb, I., Lämmermann-Barthel, J., Hinderer, M., Ellwanger, D., & Frechen, M. (2004): Sediment budget of Pliocene and Quaternary unconsolidated deposits of the Rheingletscher area, Swiss Midlands and the Upper Rhine Graben. – In: DFG (Hrsg.) Abstract Volume, IODP - ICDP Joint Colloqium, 17.–19. March 2004, University Bremen: 4 S.

Penck, A. & Brückner, E. (1901/09): Die Alpen im Eiszeitalter, 1199 S.; Leipzig (Tauchnitz).

Preusser, F. (2009): Stratigraphische Gliederung des Eiszeitalters in der Schweiz. – Jahresberichte und Mitteilungen des oberrheinischen Geologischen Vereins, N.F., 92: 83–98; Stuttgart.

Preusser, F., Graf , H.R., Keller, O., Krayss, E. & Schlüchter, Ch. (2011): Quaternary glaciation history of northern Switzerland. – Eiszeitalter und Gegenwart / Quaternary Science Journal, 60/2: 282–305; Hannover.

Rolf, C. (1992): Statistische Untersuchungen zur Zuverlässigkeit magnetischer Untersuchungen mit dem Spinnermagnetometer an Sedimentproben aus Oberschwaben. – Niedersächsisches Landesamt für Bodenforschung – Geowissenschaftliche Gemeinschaftsaufgaben, Bericht Ar.-Nr. 110230, 11 S.; Hannover.

Schädel, K. (1950): Untersuchungen über das Altdiluvium des Rheingletschers zwischen Iller und Bodensee. – Dissertation Universität Tübingen: 169 S.; Tübingen.

Schädel, K. (1953): Die Stratigraphie des Altdiluvium im Rheingletschergebiet. – Jahresberichte und Mitteilungen des oberrheinischen Geologischen Vereins, N.F., 34: 1–20; Stuttgart.

Schädel, K. & Werner, J. (1963): Neue Gesichtspunkte zur Stratigraphie des mittleren und älteren Pleistozäns im Rheingletschergebiet. – Eiszeitalter und Gegenwart, 14: 5–26; Öhringen.

Schaefer, I. (1965): The Succession of fluvioglacial Deposits in the Northern Alpine Foreland. – University of Colorado Studies, Series of Earth Sciences, 7: 9–14; Boulder.

Schirmer, W. (1995): Regional field trips: Rhein-Traverse. – Quaternary field trips in Central Europe: 475–558; München.

Schreiner, A. (1982): Sedimente aus vier Eiszeiten in der Altmoräne des Rheinvorlandgletschers in der Forschungsbohrung Seibranz 1981 (Baden-Württemberg). – Jahreshefte des Geologischen Landesamts Baden-Württemberg, 24: 121–130; Freiburg.

Schreiner, A. (1989): Zur Stratigraphie der Rißeiszeit im östlichen Rheingletschergebiet (Baden-Württemberg). – Jahreshefte des Geologischen Landesamts Baden-Württemberg, 31: 183–196; Freiburg.

Schreiner, A. (1992): Geologische Karte von Baden-Württemberg 1:50.000. Erläuterungen zu Blatt Hegau und westlicher Bodensee. – 290 S.; Freiburg, Stuttgart (Landesvermessungsamt Baden.Württemberg).

Schreiner, A. (1997): Einführung in die Quartärgeologie. – 257 S.; Stuttgart (Schweizerbart).

Schreiner, A. (2003): Deckenschotter im Hegau und am westlichen Bodensee. – Zeitschrift der Deutschen Geologischen Gesellschaft, 154, 2/3: 357–368. Stuttgart.

Schreiner, A. & Ebel, R. (1981): Quartärgeologische Untersuchungen in der Umgebung von Interglazialvorkommen im östlichen Rheingletschergebiet (Baden-Württemberg). – Geologisches Jahrbuch, A 59: 3–64; Hannover.

Schreiner, A. & Haag, T. (1982): Zur Gliederung der Rißeiszeit im östlichen Rheingletschergebiet (Baden-Württemberg). – Eiszeitalter u. Gegenwart, 32: 137–161, Hannover.

STD (2002): Stratigraphische Tabelle von Deutschland 2002. – Deutsche Stratigraphische Kommission (Hrsg.), Potsdam (GeoForschungsZentrum); Frankfurt a. M. (Forschungs-Institut Senckenberg). Internet-Publ.: http://www.stratigraphie.de/std/index.html

Steininger, F.F. & Piller, W.E. (eds.) (1999): Empfehlungen (Richtlinien) zur Handhabung der stratigraphischen Nomenklatur. – Courier Forschungsinstitut Senckenberg, 209: 19 S., Frankfurt.

Szenkler, C., Bertleff, B. & Ellwanger, D. (1997): Glacial sedimentology, glaciotectonics and erosional events in the Singen basin complex and its hydrogeological consequences (South German Alpine Foreland, Lake Constance area). – Gaea heidelbergensis, 3: 328–329; Heidelberg.

Szenkler, Ch. & Bock, H. (1999): Quartärgeologie und Rohstoffgeologie im Singener Beckenkomplex. Westliches Rheingletschergebiet (Hegau, Lkrs. Konstanz). – Jahresberichte und Mitteilungen des oberrheinischen Geologischen Vereins, N.F., 81: 183–216; Stuttgart.

Verderber, R. (1992): Quartärgeologische Untersuchungen im Hochrheingebiet zwischen Schaffhausen und Basel. – Dissertation Universität Freiburg: 183 S.; Freiburg i. Br.

Verderber, R. (2003): Quartärgeologie im Hochrheingebiet zwischen Schaffhausen und Basel). – Zeitschrift der Deutschen Geologischen Gesellschaft, 154, 2/3: 369–406; Stuttgart.

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Quaternary Stratigraphy of Southern Bavaria

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Abstract: A review of current stratigraphical systems for the Quaternary sedimentary sequences of Southern Bavaria is given as it is used by the Geological Survey of the Bavarian Environment Agency. Different classification approaches for continental deposits of the Quaternary are highlighted with a special focus on the climate and terrace stratigraphy which are commonly used in Bavaria. A description of the associated informal units documents the current status of application and may lead to formal definitions. In Bavaria the traditional classification after Penck & Brückner (1901–1909) with its completions and refinements is still in use. New results concerning a more detailed structuring of the glacial epoch by subordinate cold and warm phases were integrated into this system. Terrace sequences are crucial for this classification of the Quaternary in Southern Bavaria whose chronological interpretation is the base of the so-called morphostratigraphy. Successions of terminal moraines which constitute glacial-glaciofluvial sequences with the associated terraces represent a second basis of stratigraphical division. Therefore, beside a detailed documentation of the terrace units also classifications of different terminal moraines are presented. Further stratigraphical systems are used in Bavaria and in adjacent areas which are based on different criteria or which lead to different chronological classifications. Even the described stratigraphical classifications are not used by all authors in the same way. The documentation of the current use may assist a coordination of different nomenclatures for the users benefit.

[Quartärstratigraphie von Südbayern]

Kurzfassung: Eine Übersicht der aktuellen stratigraphischen Bezeichnungen für die quartäre Schichtenfolge Südbayerns wird gegeben, wie sie am Geologischen Dienst des Bayerischen Landesamts für Umwelt in Verwendung ist. Unterschiedliche stratigraphische Gliederungsansätze für kontinentale Quartärablagerungen werden vorgestellt und die klimatostratigraphische Einteilung sowie die Terrassenstratigraphie als in Bayern meistverwendete Varianten näher ausgeführt. Die Beschreibung der zugehörigen, bisher informellen Einheiten bezweckt eine Dokumentation des jeweiligen Stands der Verwendung und kann womöglich formelle Definitionen vorbereiten. Die klimatostratigraphischen Einheiten sollen den gesamten Zeitraum des Quartärs lückenlos abdecken und vertreten derzeit überregionale, formelle Stufenbezeichnungen. In Bayern wird weiterhin die klassische Gliederung nach Penck & Brückner (1901–1909) mit ihren Erweiterungen verwendet. Neue Erkenntnisse über eine stärkere Gliederung des Eiszeitalters durch untergeordnete Kalt- und Warmphasen werden in dieses System integriert. Für diese Gliederung des Quartärs in Südbayern ausschlaggebend sind zum Einen die Terrassentreppen, deren zeitliche Interpretation eine Grundlage der sogenannten Morphostratigraphie bildet. Die zweite Grundlage bilden Endmoränengirlanden, die mit den davon ausgehenden Terrassen glazial-glazifluviale Sequenzen (‚Glaziale Serien') bilden. Neben der ausführlichen Dokumentation der Terrassen-Einheiten, werden deshalb auch verschiedene Endmoränen-Gliederungen vorgestellt. Weitere Nomenklaturen, die auf anderen Kriterien beruhen oder zu anderen chronologischen Einstufungen gelangen, sind für Bayern oder in den angrenzenden Ländern in Gebrauch. Auch die beschriebenen stratigraphischen Gliederungen werden nicht von allen Bearbeitern in gleicher Weise verwendet. Die Dokumentation der derzeitigen Verwendung soll eine Abstimmung dieser Nomenklaturen im Interesse der Nutzer fördern.

Keywords: *Quaternary stratigraphy, climate stratigraphy, terrace stratigraphy, moraine stratigraphy, Southern Bavaria, Germany, Alpine Foreland*

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1 Introduction

More than 100 years of investigation of Quaternary deposits in the northern Alpine region led to numerous proposals for classification of the sediments accumulated during the Pleistocene epoch (Fiebig et al., in press). Hence, a hardly manageable number of different nomenclatures evolved, often accompanied by different use of synonymic terms. Against this background the 'Arbeitsgemeinschaft Alpenvorlandquartär' (AGAQ; Working Group on the Quaternary of the Alpine Foreland) aims at documenting and defining stratigraphic systems and terms used in the northern Alpine region in order to make them better comparable. This paper intends to present a stratigraphical standard classification for the Bavarian Alpine Foreland as it is currently used in the Geological Survey (Bavarian Environment Agency). References to different applied glossaries shall give assistance for understanding the diversity of nomenclatures in the relevant literature. For a better understanding of the primary literature we consequently use the original german terms in this paper.

The application of the 'International Stratigraphic Guide' (Salvador 1994) and resulting suggestions (Steininger & Piller 1999) for continental quaternary deposits raises some trouble. They show very small-scaled changes in facies and also pronounced hiatuses. Thus there is a need for high chronological resolution, but at the same time there is a lack of appropriate dating methods for the older parts of the Quaternary (Preusser et al. 2008).

Table of content

2 Stratigraphical systems

Murphy & Salvador (1999) distinguish five essential categories of stratigraphic classifications dependent on the criteria applied for the discrimination of each unit:

(i) lithostratigraphy,
(ii) stratigraphy by unconformity bounded units,
(iii) biostratigraphy,
(iv) magnetostratigraphy,
(v) chronostratigraphy.

All those different kinds of stratigraphical classification – and further comparables – can be applied in different ways to organise the Quaternary.

The marine oxygen isotope stages (MIS) and the magnetostratigraphy serve as an international reference scale for a chronological classification of the Quaternary (Crowhurst 2002, Ogg & Smith 2004). The contribution of magnetostratigraphical investigations to the stratigraphical classification of Quaternary deposits in Bavaria is limited due to generally short and fragmentary sediment sequences (Strattner & Rolf 1995; Hambach et al. 2008).

The MIS provide a detailed classification of the marine Quaternary, reflecting changes in sea water temperatures and global ice volume (Crowhurst 2002). Currently the MIS display the most common international reference scale for the classification of Quaternary deposits. However, correlation with continental sedimentary units and climatic phases is not straightforward and difficult without numeric ages of the continental sequences.

2.1 Chronostratigraphy and comparable stratigraphic systems

Validating the Quaternary as the youngest period/system of the Earth's history and the expansion of its lower boundary to 2.58 Ma by the International Union of Geological Sciences (IUGS) (Gibbard et al. 2009) paid regard to a long existing usage in many regions with continental Quaternary deposits and also in Bavaria. The subdivision of the Pleistocene in subseries/subepochs (Lower/Early, Middle, Upper/Late Pleistocene) is still in progress (Litt et al. in prep.). Like the base of the Quaternary (base of Gelasian) the boundary between Lower/Early and Middle Pleistocene is linked to a polarity change of the Earth's magnetic field, the transition from Matuyama (reversed) to Brunhes epoch (normal). This demarcation indeed is traceable throughout the world. However, it is disconnected from the commonly applied main climate stratigraphical classification because a correlation of climate and polarity changes is not expected.

Internationally established Quaternary stages only exist for marine deposits. In continental environments a chronostratigraphical classification is often replaced by a regional climate stratigraphy differentiating cold and warm phases. Even without a formal definition this phases often are used like chronostratigraphical stage terms (e. g. 'Saalian', 'Eemian').

2.2 Biostratigraphy

Biostratigraphically significant locations of the Quaternary in Bavaria are summarised in Table 1. The stratigraphical classification of the warm-temperate phases of the Pleistocene and the Holocene is essentially based on palynological analyses which are summarised in Drescher-Schneider et al. (2001).

The current mammalian stratigraphy for the Pleistocene in Germany is largely based on small mammal remains (Koenigswald & Heinrich 2007). They are better suitable because of their faster evolutionary development (Koenigswald 2002). But like the remains of large mammals, localities enriched in small mammals are very rare. This holds particularly true for deposits older than Upper Pleistocene.

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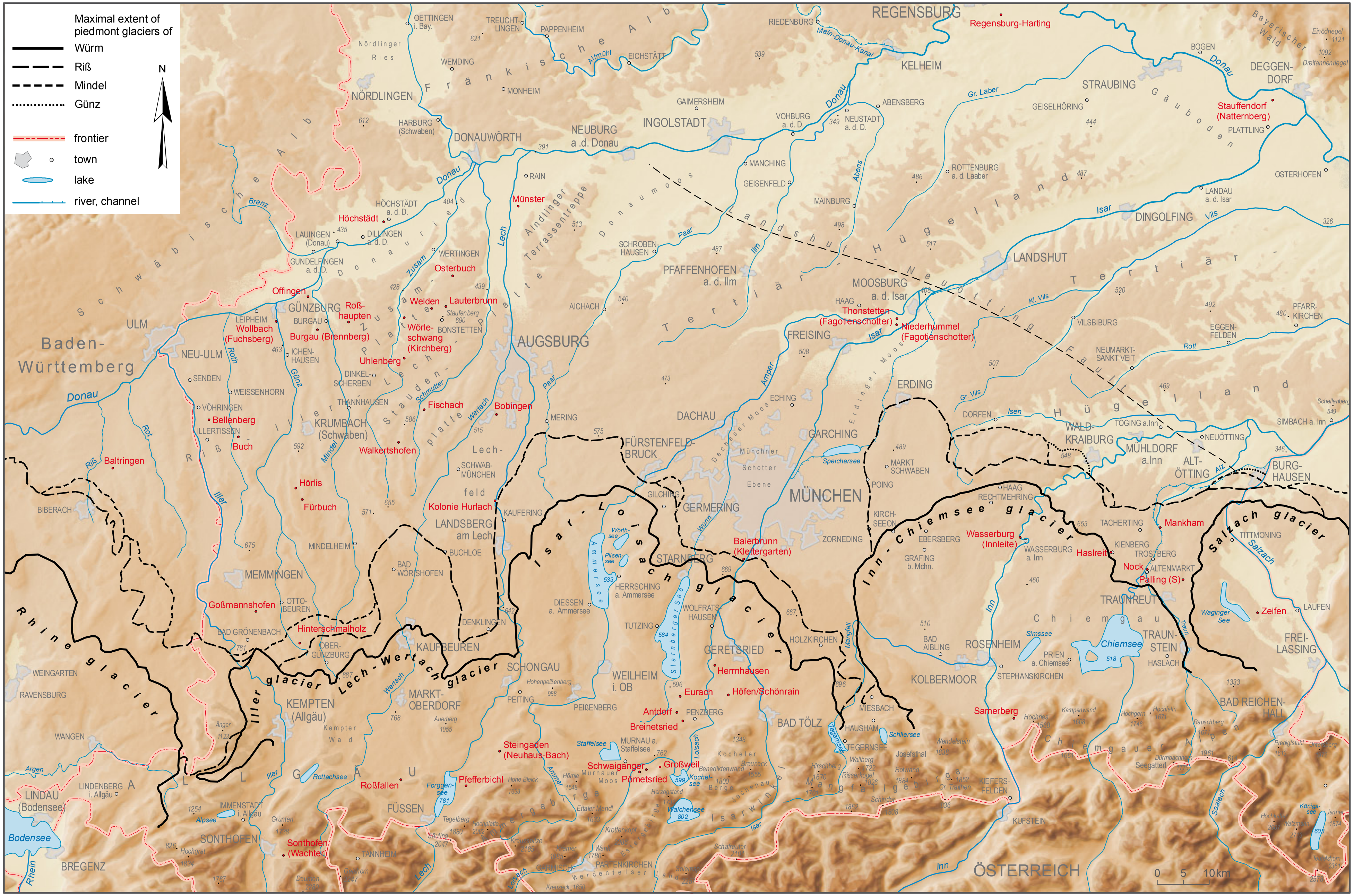

Fig. 1: Overview of the Bavarian Alpine Foreland and adjacent areas including the names of landscapes and sites mentioned in the text.

Abb. 1: Übersicht des bayerischen Alpenvorlands und seiner Nachbargebiete mit im Text erwähnten Landschaftseinheiten und Lokalitäten.

Tab. 1: Biostratigraphically important localities of the Pleistocene in Southern Bavaria. Codes for geological units composed of stratigraphy and facies/lithology; the code of the unit containing the fauna or flora in bold characters; Stratigraphic codes: B = Biber; D = Donau; M = Mindel; M/R = Mindel/Riß; OSM = Upper Freshwater Molasse (Obere Süßwassermolasse); qh = Holocene; R = Riß; Rj = Jungriß; R/W = Riß/Würm; USM = Lower Freshwater Molasse ('Untere Süßwassermolasse'); W = Würm; Wf = early Würm ('Frühwürm'). Facial /lithologic codes: ,,f = fluvial; ,,fl = solifluction loam; ,,g = morainic; ,G = gravel; ,H = peat; ,Hp = compressed peat ('Schieferkohle'); ,,l = lacustrine; ,K = lime ('sinter', 'chalk'); ,Kq = solid sinter ('Kalktuff'); ,Lo = loess; ,Lol = loess loam; ,M = marl; (,M) = clod(s) of marl; ,p = periglacial, ↑ = succession.

Tab. 1: Biostratigraphisch bedeutsame Lokalitäten im Pleistozän des Bayerischen Alpenvorlands.

Tab. 1a: Palynological localities.

Tab. 1a: Fundorte mit Pollenfloren.

TK25	Locality	Coordinates	Bedding	Ecology/ interpretation	Classification	Reference
7726	Bellenberg	3582200 5347100	,Lo-,,fl with ,**H** / W,G,p / OSM	glacial	Würm pleniglacial	Peschke (1982, unpubl. report)
8027	Goßmannshofen	3592700 5310400	,,fl / ,**H** / R,G	glacial	Würm	Frenzel (1974, unpubl. report)
8427	Sonthofen (Kgr. Wachter)	3599850 5263500	W,,g / W,G / ,**Hp in W,,l** / R,G+R,,g	interstadial	Early Würm	Peschke (1983a)
8233	Antdorf	≈4449850 ≈5291650	W,,g / W,G / W,,l with ,**Hp**	interstadial	Early Würm	Peschke (1983a)
8333	Pömetsried	4442650 5280150	W,G / ,**Hp** / W,,l	interstadial	Early Würm	Reich (1953); Peschke (1983a)
7939	Wasserburg, verschiedene Fundorte	≈4516200 ≈5325500	W,G with ,**Hp**	interstadial	Early Würm	Frenzel & Jochimsen (1972)
8234	Breinetsried	4451200 5289900	W,G with ,**Hp**	interstadial	Early Würm: Moershoofd?	Peschke (1983a)
8234	Höfen/Schönrain	4459810 5295030	W,G with ,**Hp**	interstadial	Early Würm	Peschke (1983a)
8333	Schwaiganger	≈4444000 ≈5280600	W,G with 2 ,**Hp**	interstadial	Early Würm: Odderade? Brørup?	Peschke (1983a)
8329	Roßfallen	≈4396500 ≈5278650	W,,g / ,**Hp** + W,,l / USM	interstadial terminal interglacial ↑	Early Würm end of Riß/Würm	Stritzke (1996, unpubl. report) correlated to Pfefferbichl
8331	Steingaden	4415600 5284150	W,,g / **Wf-R/W,,l**	interstadial terminal interglacial ↑	Early Würm end of Riß/Würm	Höfle & Müller (1983)
8330	Pfefferbichl	4409150 5277460	W,,l / ,**Hp** / R,,l	glacial interglacial ↑	Würm Riß/Würm	Reich (1953); Frenzel (1976)
8333	Großweil	≈4446600 ≈5281100	W,G / Wf-R/W,,l with ,**Hp** / R,G+S	interstadial interglacial ↑	Early Würm Riß/Würm ↑	Reich (1953); Peschke (1976)
8239	Samerberg 1	4515150 5290350	W,,g / **Wf-R/W,,l** / R,,g / ?M,,l / M,,g	interstadial interglacial↑	Early Würm Eem (= Riß/Würm) ↑	Grüger (1979)
8134	Herrnhausen	≈4457200 ≈5300750	W,,g / W,G / ,**Hp** / Rj,,l / R,,g	interglacial glacial ↑	Riß/Würm Riß ↑	Peschke (1983b)
8042	Zeifen	4562100 5310910	W,G / **Rj-R/W,K,l**	interglacial glacial ↑	Riß/Würm Riß ↑	Jung et al. (1972)
8234	Eurach	≈4450500 ≈5294750	W,G / **Rj-R/W,K,l**	interglacial glacial ↑	Riß/Würm Riß ↑	Beug (1979); Jung (1979): macro remains
7039	Regensburg-Harting (BMW)	≈4512500 ≈5426500	?Ra,G / ,**H** / ?,G	interglacial	Middle Pleistocene?	Grosse-Beckmann (1993)
8239	Samerberg 2	4514800 5290760	W,,g / Wf-R/W,,l / R,,g / R-**M/R,K**-M,,l / M,,g	interglacial - interstadial	Holstein II (= ??) Holstein (= Mindel/Riß)	Grüger (1983)
7629	Uhlenberg	4397200 5360100	,Lol-,,fl / ,**Hp** / ,M,f / D,G	interglacial	<Tegelen, > Cromer Bavel?	Schedler (1979); Bludau (1995)

Tab. 1b: Malacological or mammal localities.

Tab. 1b: Fundorte mit Mollusken- oder Kleinsäugerfaunen.

TK25	Locality	Coordinates	Bedding	Ecology/interpretation	Classification	Reference
	Molluscs:					
8427	Sonthofen (gravel pit "Wachter")	3599850 5263500	W,,g / W,G / ,**Hp in W,,l** / R,G + R,,g	interstadial	Early Würm	Dehm in Ebel (1983)
7831	Kolonie Hurlach	4414730 5332570	qh,G / **R/W,Kq**	interglacial	Riß/Würm	Kovanda (1989)
7329	Höchstädt	4393200 5386500	,Lo / (,**M**) in R,G	interglacial or interstadial (warm)	?Inner-Riß	Puissegur in Leger (1988)
7331	Münster	4419200 5389500	(,**M**) in R,G	interglacial	Pleistocene	Tillmanns et al. (1982); Rähle (1994, unpubl. report)
7731	Bobingen	4415000 5349250	,Lo /,,fl / (,**M**) in R,G	interglacial	Older than Eem	Rähle (1994, unpubl. report)

8234	Eurach	≈4450650 ≈5294760	W,G / **Rj-R/W,K,l**	interglacial	Riß/Würm or Pre-Mindel ?	Dehm (1979); Ohmert (1979): Ostracoden; Kovanda (2006)
7537	Thonstetten (Fagotienschotter)	4492400 5367800	,Lo / ,,fl /,**S** in ?R,G or ?G,G	interglacial, river + floodplain	Older than Mindel?	Brunnacker & Brunnacker (1962); Kovanda (2006)
7537	Niederhummel (Fagotienschotter)	4492350 5366600	,Lo / ,,fl / ,**M,f** / ?R,G or ?G,G	interglacial, river + floodplain	Older than Mindel?	Brunnacker & Brunnacker (1962); Kovanda (2006)
7629	Uhlenberg	4397200 5360100	,Lol-,,fl / ,Hp / ,**M,f** / D,G	interglacial; floodplain	Tiglian?, possibly Waal? ≈Buch?	Rähle (1995)
7530	Lauterbrunn	4405250 5370100	,Lol+,,fl / **D,G**	interglacial; floodplain	Tiglian?, possibly Waal? ≈Buch?	Rähle (1995)
7828	Fürbuch	3600810 5332390	D,G / ,,**f** (reloc. OSM)	???	Pleistocene	Münzing (1974)
7828	Hörlis	3599450 5334550	D,G / (,**M**) / B,G,p	interglacial, humid deciduous forest + river	before Riß/Würm	Münzing (1974)
7727	Buch	?3588000 ?5344000	D,G / ,**M** / B,G,p	interglacial, humid deciduous forest, floodplain	Early Pleistocene	Schröder & Dehm (1951) Münzing & Ohmert (1974)
7528	Brennberg/Burgau	3602450 5365280	(,**M**) in B,G,p (Urdonau)	interglacial	Pleistocene	Münzing in Löscher et al. (1978)
7529	Kirchberg/Wörleschwang	4397200 5367950	(,**M**) in B,G,p (Urdonau)	interglacial	Pleistocene	Münzing in Löscher et al. (1978)
7529	Fuchsberg/Wollbach	3594430 5366580	D,G (Mischfazies)/ (,**M**)/B,G,p	interglacial, deciduous forest – alluvial forest	Pleistocene	Münzing & Aktas (1984)
7530	Welden	4402500 5369720	D,G (Mischfazies) / (,**M**) / B,G,p	interstadial	Pleistocene	Münzing & Aktas (1984)
7430	Osterbuch	4406570 5376040	(,**M**) in D,G	interglacial, deciduous forest – alluvial forest	≈ Buch	Münzing & Aktas (1984)
7729	Walkertshofen	?4396100 ?5343850	B,G with (,**M**)	interstadial or early interglacial?	≈ Fischach / Buch	Eberl (1930: 309)
7730	Fischach	?4401060 ?5350150	B,G with (,**M**)	interstadial or early interglacial? floodplain	„Altpleistozän"; ≈ Buch	Schröder & Dehm (1951)
	Small mammals:					
7629	Uhlenberg	4397240 5360150	,Lol-,,fl / ,Hp / ,**M,f** / D,G	---	Villanyium, MN 17 (corr. youngest Tiglian)	Ellwanger et al. (1994)

Mollusc faunae provide the opportunity for correlations with climate stratigraphy of the Nordic glaciations (Dehm 1979, Münzing & Aktas 1987, Rähle 1995, Kovanda 2006). However, a distinct classification system with typical communities or type fossils (Lozek 1964) is not established.

For other zoological taxa no biostratigraphical classification systems are established for the continental Quaternary so far. However, a relative stratigraphical correlation is partly feasible when accompanied by additional investigations (e. g. isotopic analyses on ostracodes by Grafenstein et al. 1992).

2.3 Lithostratigraphy and comparable classification systems

In Bavaria the traditional classification systems (with some further adjustments) are still applied. According to the original classification of Penck & Brückner (1901–1909) primarily morphological aspects were in the focus which later led to the term 'morphostratigraphy'. However, the base forming concept of the 'Glaziale Serie' and 'Glazialer Komplex' (glacial-glaciofluvial sequences of one glacial phase respectively of one ice advance) introduced by Penck & Brückner (1901–09: 13f) also contains litho-facies aspects.

Lithostratigraphy.
At present a lithostratigraphical system for the deposits of the South German Quaternary is only applied in Baden-Württemberg in the area of the Pleistocene Rhine glacier. Its framework is primarily based on the observed succession of basin fills (Ellwanger et al. 2003).

Morphostratigraphy.
The classification into different 'Glaziale Serien' is the base of the climate stratigraphical classification (glacials and interglacials) and as well of a subdivision into 'morphostratigraphic' units with regard to moraine and meltwater deposits (terraces).

The terrace stratigraphy primarily uses the relative altitudinal position of meltwater deposits and – in second order – the composition of the gravel deposits and their covering strata. This led to terms like 'Niederterrasse' (Lower Terrace), 'Hochterrasse' (Higher Terrace) or 'Deckenschotter' (Cover Gravel). In addition distinct local terms are used in different valley systems (e. g. 'Altstadtstufe' of the river Isar at Munich).

Moraine stratigraphy uses different terminal moraine stages in connection with their respective gravel plains. Differences in relief and depth of weathering play an important role for categorisation. A supra-regional classification is only used for the terminal stages of 'Hochwürm' (Wuerm pleniglacial).

Pedostratigraphy.
A stratigraphic classification similar to the lithostratigraphic one was based on palaeosols in younger loess sequences by Semmel (1968), Bibus (1974) and Zollinger (1991). It was established north of the Alpine Foreland where high

Tab. 2: Pedostratigraphy of the younger Pleistocene of Southern Germany; chronology and classification of the palaeosols older than Riß/Würm (= Eemian) are still uncertain. Bimstuff = pumice tuff; Bt = argic horizon; (Nass-)Boden = (initial hydromorphic) soil; Humuszone = humous horizon; Taschenboden = involution layer (soil relics in hollow moulds); Tundragley = cryic gleysol.

Tab. 2: Pedostratigraphische Einheiten des jüngeren Pleistozäns zur Verwendung im Alpenvorland.

Climate stratigraphy		**Loess soils**	**Gravel soils**
		Semmel (1968); Bibus (1974); Zollinger (1991); Bibus (2002)	Bibus & Kösel (2001)
Holocene		recent soil	recent soil
Würm	Oberes Würm (Upper / Late Würmian)	(Laacher Bimstuff) Erbenheimer (Nass-)Boden E4 (Eltviller Tuff) Erbenheimer (Nass-)Boden E3 Erbenheimer (Nass-)Boden E2 Erbenheimer (Nass-)Boden E1 (Rambacher Tuff)	
	Mittleres Würm (Middle Würmian)	Lohner Boden / Böckinger Boden Tundragley Gräselberger Boden	
	Unteres Würm (Lower / Early Würmian)	Niedereschbacher Zone Obere Moosbacher Humuszone Mittlere Moosbacher Humuszone Untere Moosbacher Humuszone	
Riß /Würm	(= Eemian)	1st fossile Bt (Eem-Boden)	Rosnaer Boden
Riß	Jungriß	Bruchköbeler (Nass-)Boden B6 Bruchköbeler (Nass-)Boden B5 Bruchköbeler (Nass-)Boden B4 Bruchköbeler (Nass-)Boden B3 Bruchköbeler (Nass-)Boden B2 Bruchköbeler (Nass-)Boden B1 Ostheimer Zone Obere Weilbacher Humuszone	
	?Mittel/Jungriß	2nd fossile Bt	Baltringer Boden
	Mittelriß	Tundragley 2 Tundragley 1 Allschwiler Zone (Reinheimer Tuff) Heilbronner (Reinheimer) Humuszone	
	?Alt/Mittelriß	3rd fossile Bt (Biesigheim)	'Taschenboden' v. Bittelschieß
Mindel /Riß	Altriß (= Holsteinian)	4th fossile Bt	Neufraer Boden
Mindel			

resolution sequences are available. But even older terms with stratigraphic content are in use (Brunnacker 1953, 1982; Fink 1956). A recent stratigraphical differentiation of distinct interglacial soils in gravel deposits was carried out by Bibus & Strahl (2000) or Bibus & Kösel (2001) in the Rhine glacier area and the Bavarian-Swabian Danube valley.

3 Regional Quaternary stratigraphy of Southern Bavaria

Table 3 provides a short outline of the current Quaternary stratigraphy of Southern Bavaria. It is used particularly at the Geological Survey of the Bavarian Environmental Agency and largely also at Bavarian universities. Localities mentioned in the following text are given in Figure 1.

For a long time two different boundaries were applied in continental environments between the Pliocene and the Pleistocene:

(i) the internationally defined lower boundary of the Calabrian at 1.8 mio. yrs at the Vrica-section (Aguirre & Pasini 1985) or

(ii) the boundary which is common in Central and NW Europe and which is connected to the first cooling phase in the Lower Rhine area (Praetiglian, Zagwijn 1989) near the magnetic polarity change between Gauss and Matuyama epoch, currently at 2.58 Ma.

The alternating use of both boundaries in former publications may cause misunderstandings. For example the lower parts of the 'Uhlenberg section' were classified into the Pliocene by Ellwanger et al. (1994) but to Early Pleistocene by Doppler & Jerz (1995), whereupon the chronological ideas do not disagree. Other occurrences assigned to the Pliocene by former authors (e. g. Eberl 1930) were soon reclassified into the Quaternary. The reasons are mostly lithological affinities to other deposits of the Pleistocene and palaeogeographical considerations. A secure classification based on relative or numerical ages is so far only sporadically possible.

A division of the Pleistocene into the subseries Lower, Middle and Upper Pleistocene (= subepochs Early/Middle/Late) is internationally established. In Bavaria a slightly different subdivision is used based on the regional climate stratigraphical classification (Tab. 3).

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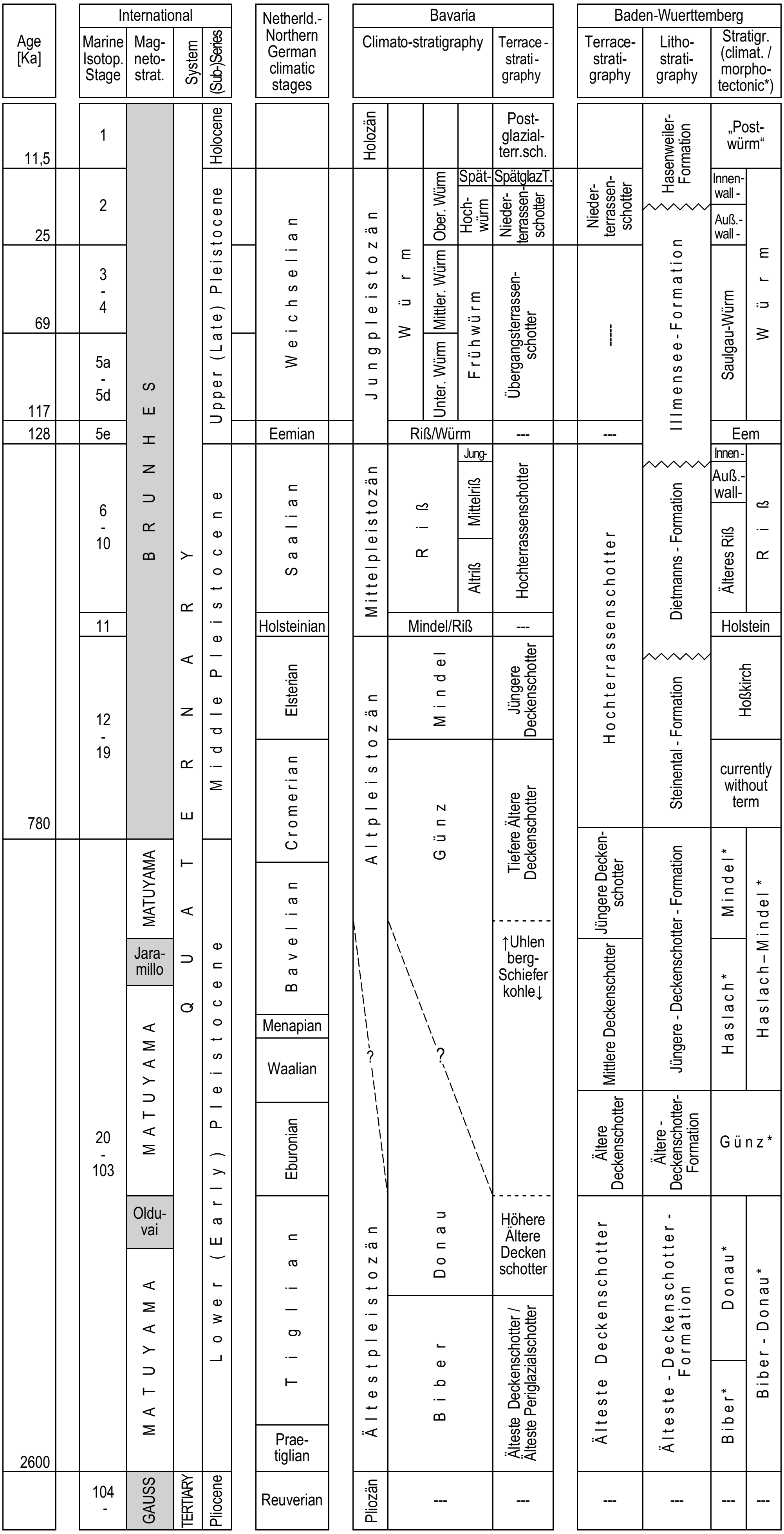


Tab. 3: Stratigraphic systems for the Quaternary of Southern Bavaria according to the Deutsche Stratigraphische Kommission (2002), Ogg & Smith (2004), Ellwanger et al. (2003). Of the Bavarian climate stratigraphic terms only the Würmian age/stage is formally defined by Chaline & Jerz (1984). Therefore we will not use the ending 'ian' for all our terms consequently; ↑↓ = stratigraphic position unsure.

Tab. 3: Stratigraphische Tabelle des Quartärs in Südbayern.

3.1 Climate stratigraphy for Southern Bavaria

3.1.1 Biber ('Biberian')

First description.
At the INQUA-Congress 1953 in Rome and Pisa Schaefer (1955) presented a second extension of the formerly tetraglacial system of Penck & Brückner (1901/09). He assigned the gravel deposits of the 'Staufenbergschotter' (chronologically classified as 'Donau' by Eberl 1930) and of the 'Aindlinger Terrassentreppe' to a new glacial epoch named after the creek Biberbach north of Augsburg. By this, he followed the system of Penck who labeled the glacial periods of the Quaternary using the names of rivers in descending alphabetical order from older to younger units.

Current application.
The term 'Biber' is currently used for the oldest period of the Bavarian Pleistocene ('Oldest Pleistocene') when the 'Ältester Deckenschotter' ('Oldest Cover Gravel') and probably also the 'Ältester Periglazialschotter' ('Oldest Periglacial Gravel') were accumulated. These include:

(i) gravel deposits like the 'Staufenbergschotter' near Bonstetten (NW of Augsburg),
(ii) the 'Hochschotter' and some lower gravel accumulations at the eastern border of the 'Aindlinger Terrassentreppe' (SW of Neuburg/Donau),
(iii) the wide-spread accumulation of the 'Staudenplattenschotter' (SW of Augsburg), which was assigned to the 'Donau' by Schaefer 1957,
(iv) the oldest periglacial gravel deposits in the Allgäu and in the area of the river Danube which are probably of similar age.

The 'Älteste Deckenschotter' are assumed to be connected to a first pronounced cold climatic stage following the Pliocene. But so far there is no direct evidence. However, the resemblance of the 'Älteste Deckenschotter' with younger glaciofluvial sediments argues for an accumulation during a phase of extended alpine glaciers. Also, the existence of large cobbles (up to ~25 cm) indicates a relatively close glacier front reaching into the foreland area.

The end of the 'Biber' coincides with the period of shifting pathways of the 'proto-Iller' from the area of the 'Staudenplatte' to the adjacent region of the 'Zusamplatte' in the Northwest. It remains doubtful, if the last episode of the 'Biber' coincides with a warm phase documented in the 'Bucher Schneckenmergel' or further flood deposits (see below).

Type region and occurrence.
The gravel deposits of the 'Staufenbergterrasse' and the 'Staudenplatte' are suggested as the 'Biber' type locality. Furthermore the remaining 'Älteste Deckenschotter' and the 'Älteste Periglazialschotter' including isolated fine-grained flood deposits like the 'Bucher Schneckenmergel' are classified as 'Biber' (see also 3.2.2). These sediments occur as isolated relics on the top of the 'Älteste Periglazialschotter' below the 'Höhere Ältere Deckenschotter' (level of the 'Zusamplatte', see 3.2.3) and contain interglacial mollusc remains (Münzing & Aktas 1986). These sequences occur on the Iller-Lech alluvial plain in the western part of the Alpine Foreland. East of the 'Aindlinger Terrassentreppe' no sediments corresponding with Biberian age were found so far.

Dating and references.
At present no numeric ages for the 'Biber'-type deposits are available. Mollusc-bearing reworked clods/lumps of marl in the 'Staudenplattenschotter' and at the top of the 'Älteste Periglazialschotter' enable just a correlation from Tiglian to Holsteinian after Münzing & Aktas (1987). However, Rähle (1995) assumes a late Tiglian age for the fauna of the 'Uhlenberg' section which has to be younger than the Biber type deposits according to terrace stratigraphical relations. Hence the faunae of 'Biber'-type deposits must be older than the late Tiglian.

3.1.2 Donau ('Danubian')

First description.
The glacial period 'Donau', that means a corresponding complex of three cold phases was introduced by Eberl (1930) for gravel deposits which are located in a morphologically higher position than the 'Ältere Deckenschotter' near Memmingen. The latter are classified into the 'Günz' after Penck & Brückner (1901–1909). Eberl (1930) followed the nomenclature of Penck (river names in alphabetical order) but with the Danube (Donau) he used a river outside his own investigation area, the southern Iller-Lech alluvial plain. According to Eberl (1930: 390, Tab. II) three 'Donau' stages correlate with minima of the Milanković-curve between 800 and 650 ka.

Current application.
The extent of the gravel deposits attributed to the 'Donau' glacial period has changed significantly since Eberl (1930) predominantly as a result of the investigations of Schaefer (1955) and Löscher (1976). Currently the period of deposition of the widespread 'Zusamplattenschotter' and its equivalents in the area of the Riß-Lech alluvial plain or of the 'Aindlinger Terrassentreppe' is described as 'Donau'. In the scheme of terrace stratigraphy these accumulations are called 'Höhere Ältere Deckenschotter' (Higher Older Cover Gravel). They have to be discriminated from the locally underlying channel fill gravel of probably periglacial genesis ('Ältester Periglazialschotter', Oldest Periglacial Gravel) and their partly conserved covering strata.

The termination of Donau to the 'Günz', a separating interglacial, is so far unclear. The 'Uhlenberg-Schieferkohle' (compressed peat; Fig. 2) is considered to document a warm period before the 'Günz', maybe even a Donau/Günz interglacial. However, correlation with the 'Tiefere Ältere Deckenschotter' (Lower Older Cover Gravel) of 'Günz' age would be possible too.

The deposits classified as 'Donau' are interpreted as glacial meltwater deposits, although no unambiguous evidence for glaciations into the Alpine foreland during this period was found so far. Potential moraine-like deposits in the Denklinger Rothwald northwest of Schongau were classified variably during their investigation history as 'Mindel' (Penck & Brückner 1901–1909), 'Günz' (Eberl

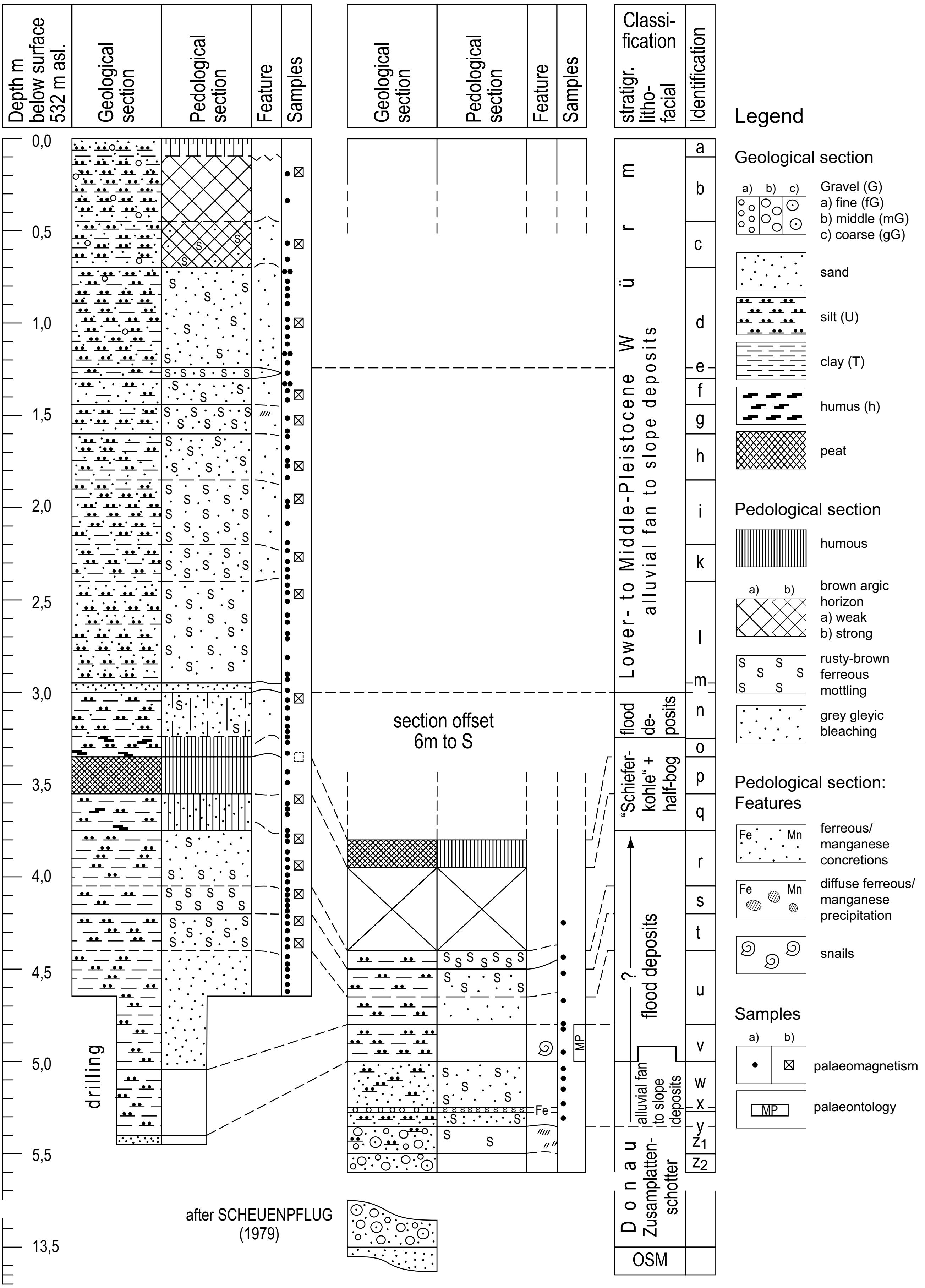


Fig. 2: Section of the covering strata of the gravel pit at Uhlenberg north of Dinkelscherben (after Doppler & Jerz 1995).

Abb. 2: Schichtenprofil der Kiesgrube am Uhlenberg N Dinkelscherben (nach Doppler & Jerz 1995).

1930: 280–281) or 'younger Donau' (Rögner 1979, 88–91). Other possibly 'Donau'-aged moraines near Bickenried at the 'Höhen über Kaufbeuren' are described by Rögner (1980). Becker-Haumann (2005) assigns these moraines to the 'Günz', based on the fact that he inserts another glacial between Günz and Mindel, the so-called Haslach.

Type region and occurrence.
The sequence of the 'Zusamplattenschotter' is suggested as 'Donau' type region. This definition excludes locally preserved underlying 'Älteste Periglazialschotter' but includes overlying flood deposits. The status of the 'Uhlenberg-Schieferkohle' (Fig. 2) which developed from the latter is still an open question. Furthermore 'Höhere Ältere Deckenschotter' on the remaining Riß-Lech alluvial plain are classified as 'Donau', also including fine grained flood deposits at some places (see 3.2.3). Further, possibly Donau-aged deposits are found in the Danube area between Regensburg and Passau. So far a clear correlation with occurrences at the Riß-Lech alluvial plain is not possible. Neither loess-derived sections nor moraine-like sediments (Rögner 1979) can clearly be assigned to the 'Donau' phase.

Dating and references.
So far numeric dating of 'Donau'-deposits is not possible. However, a relative classification based on magnetostratigraphic and biostratigraphic correlations is available.

(i) Palaeomagnetical investigations on the 'Zusamplatte' show a change from reversed to normal polarity in the lower sections of solifluctive loess loam in Roßhaupten and Lauterbrunn. It is interpreted as Matuyama/Brunhes boundary, i. e. the gravel deposits of the 'Zusamplatte' including the lower parts of their covering strata would be older than 780 ka. Normally oriented layers at the base of the Roßhaupten and the Uhlenberg section have been correlated with the Jaramillo event by Brunnacker et al. (1976). Recent results of Strattner & Rolf (1995) cannot confirm this. An age of more than 1 Ma for the gravels of the 'Zusamplatte' in this regard is still a matter of debate.

(ii) The mollusc fauna in the upper parts of the gravel deposits of the 'Zusamplatte' and their fluvial covering strata suggest a Tiglian age (Rähle 1995).

(iii) Relics of small mammals in the overlying flood deposits at Uhlenberg belong to the mammal zone MN17 (upper Villanyium) according to Ellwanger et al. (1994), which correlates with Tiglian (Königswald & Heinrich 2007).

(iv) In contrast palynological analyses of the 'Uhlenberg-Schieferkohle' above the fossil-bearing flood sediments are considered to be significantly younger. Bludau (1995) suggests a correlation with the Bavelian originally defined in the Netherlands (Zagwijn & De Jong, 1985; see Tab. 3)

Accordingly, the 'Höhere Ältere Deckenschotter' and at least the lower part of their covering strata correlate with the younger Tiglian. The upper part of the covering strata and particularly the warm period represented by the 'Uhlenberg-Schieferkohle' seem to be considerably younger. As a consequence the 'Uhlenberg' section represents one or several interglacials which may be assigned to the end of the 'Donau' or the beginning of the 'Günz' period.

3.1.3 Günz ('Guenzian')

First description.
The terms 'Günz', 'Günz-glaciation' or 'Günz ice-age' date back to Penck & Brückner (1901–1909: 110). Deposits classified as 'Günz' by these authors are the 'obere' or 'ältere Deckenschotter' (upper or older Cover Gravel), e. g. the Böhener Feld southeast of Memmingen. Penck assigned all glacial and fluvial sediments which he considered to be older than 'Mindel' to the 'Günz'. Gravel deposits in a more elevated position (e. g. at the Staufenberg) he explained by tectonic displacement.

Current application.
Currently 'Günz' is perceived as the episode between 'Donau' (including a terminal interglacial) and the 'Günz/Mindel' warm period. The chronological range of 'Günz' is specified on the basis of rare gravel deposits in the area of the Riß-Lech alluvial plain ('Tiefere Ältere Deckenschotter' = Lower Older Cover Gravel). In Bavaria, so far no interglacial deposits were found which would allow defining a boundary between Günz and Mindel.

Type region and occurrence.
For 'Günz', no well-defined type region is apparent. To avoid miscorrelation it should be located in the area of the Riß-Lech alluvial plain near the type regions of 'Donau' and 'Mindel'.

The Günz-aged 'Zeiler Schotter' west of the Iller is characterised in detail by Schreiner & Ebel (1981) and appears well distinguishable due to position and composition. For the 'Heiligenberger Schotter' near Pfullendorf – considered to be of the same age – even a connection with till is verified (Bibus et al. 1996). However, the reversed magnetic orientation of younger occurrences ('Jüngere Deckenschotter' = Younger Cover Gravel) in the Heiligenberg area raises some doubt if the meaning of 'Günz' and 'Mindel' is the same in Baden-Württemberg and Bavaria. So far no 'Günz' or 'Mindel'-aged deposits were found in Bavaria which show a reversed magnetisation.

The so-called 'Zwischenterrassenschotter' (Intermediate Terrace Gravel) in the northwest of the Iller-Lech alluvial plain (Löscher 1976) are interpreted as continuation of the 'Zeiler Schotter' by Doppler (2003). But this correlation is not ensured. Classification is ambiguous also for other occurrences in the southern Iller-Lech alluvial plain. They do not offer good opportunities for a type section neither.
However in Southern Bavaria, apart from the Iller-Lech alluvial plain more occurrences of Günz-aged 'Deckenschotter' exist. In contrast to the rest of the Alpine Foreland in the area of the 'Münchner Schotterebene' deposits classified as 'Günz' occur in a normal stratigraphical sequence of gravels underneath sediments classified as 'Mindel'. A corresponding section including interstratified palaeosols is still observable in the 'Klettergarten Baierbrunn' (climbing park) south of Munich (Jerz 1993: 33).

Gravel deposits assigned to the 'Günz' intercalated with moraine-like deposits appear in the area of the 'Hohe Altmoräne' in the northern region of the former Inn glacier between Haag and Dorfen (König 1979; Grimm in prep.). Comparable deposits extend into the area of the former

Salzach-glacier as gravel, till and basin sediments. The latter infill deeply incised channels near Trostberg according to drillhole data (Eichler & Sinn 1974; Grimm et al. 1979; Doppler 2003b). For further occurrences see chapter 3.2.4.

In contrast to the better documented 'Glaziale Serien' of younger glacials the area of the Iller-Lech alluvial plain lacks evidence of 'Günz-'moraines. Only Roppelt (1988: 17) describes a very small occurrence southeast of Obergünzburg. Till deposits corresponding with 'Günz'-aged gravel can only be found in the more distant area of the former Rhine-glacier near Heiligenberg/Pfullendorf (Bibus et al. 1996) or further away in the area of the former Inn and Salzach glacier (König 1979; Grimm et al. 1979). From Upper Austria Kohl (1998: 240, 297, 313) describes 'Günz' moraines and 'Ältere Deckenschotter' at the southern rim of the Traun-Enns alluvial plain. However, the correlation of these occurrences including the Rhine-glacier area is questionable.

Due to these uncertainties and the absence of well-defined overlying interglacial deposits the definition of a type region for 'Günz' is currently premature.

Dating and references.
So far in Bavaria neither numeric ages nor biostratigraphically evaluable localities are available for Günz-aged deposits. Palaeomagnetic analyses revealed reversed magnetisation of fine-grained sediments intercalated in moraines classified as 'Günz' near Pfullendorf in Baden-Württemberg (Fromm in Bibus et al. 1996). In contrast the analyses of loess loam on the Iller-Lech alluvial plain and of basin sediments connected to 'Günz' moraines in the valleys of rivers Alz and Traun resulted in normal polarity (Strattner & Rolf 1995). This discrepancies may be due to miscorrelations and/or the fact that 'Günz' expands beyond the Matuyama/Brunhes-boundary. This seems realistic according to the classification of the 'Donau' and the 'Uhlenberg-Interglacial'. A reliable chronostratigraphical classification and correlation to the MIS-curve is not feasible.

3.1.4 Günz/Mindel ('Günz/Mindelian')

First description and current application.
Penck & Brückner (1901–1909: 111) called the warm period between the 'Günz' and the 'Mindel' glacials 'Günz/Mindel-Interglacial'. In the current Bavarian climate stratigraphy the term 'Günz/Mindel' is still in use for this warm phase which so far is solely represented by relics of soil formation on top of Günz-aged deposits.

Type region and occurrence.
At present in the Northern Alpine Foreland no locality is suitable to define the Günz/Mindel interglacial by a pollen record. The following sections comprise parts with an assumed 'Günz/Mindel' age:

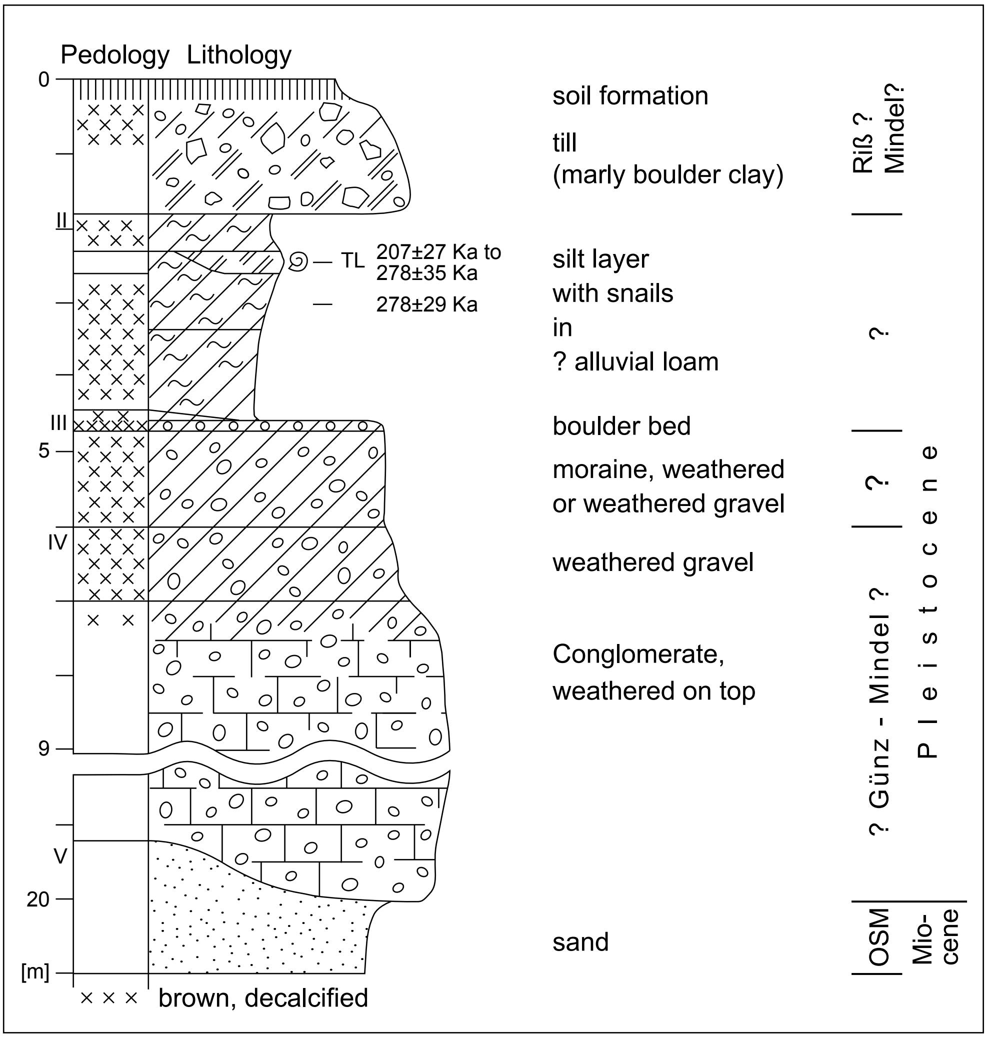


Fig. 3: Section at the ravine of Hinterschmalholz northwest of Obergünzburg after Rögner et al. (1988) and Jerz & Grottenthaler (1995). The section shows the frequent problems of Quaternary stratigraphy: stratigraphical position and partly genetical interpretation of the units are controversial.

Abb. 3: Schichtenprofil im Bachtobel von Hinterschmalholz NW Obergünzburg nach Rögner et al. (1988) und Jerz & Grottenthaler (1995).

(i) a fossil soil on meltwater deposits below an eventually 'Mindel'-aged till of the Iller-glacier in the ravine of Hinterschmalholz south of Ottobeuren (Fig. 3; Sinn 1972, Rögner & Löscher 1987, Rögner et al.1988); in contrast, a 'Riß' age is assumed for the till and a 'Mindel/Riß' age for the palaeosol by Roppelt (1988), Jerz & Grottenthaler (1995);

(ii) a fossil soil on meltwater deposits below a till of 'Mindel' (or possibly 'Riß') age of the Lech glacier in the gravel pit Rau Täle southwest of Denklingen (Rögner 1979);

(iii) geological pipes in the lowest sequence of the 'Deckenschotter' of the Isar-Loisach glacier in the 'Klettergarten Baierbrunn' south of Munich (Jerz 1993: 33, Fig. 20);

(iv) a fossil soil on proximal meltwater to moraine deposits of the Inn glacier below the 'Jüngerer Deckenschotter' in the gravel pit Osendorf south of Dorfen (Doppler & Jerz 1995: 44);

(v) a fossil soil probably below the 'Jüngere Deckenschotter' ('Vorstoßschotter') of the Salzach glacier in a road cut near Nock northwest of Altenmarkt (Doppler 2003b).

Dating and references.
Due to the lack of datable deposits reliable information on a chronological position of the warm period at the end of the 'Günz' is presently missing.

3.1.5 Mindel ('Mindelian' sensu lato)

First description.
The terms 'Mindel', 'Mindel glaciation' or 'Mindel ice-age' date back to Penck & Brückner (1901–1909: 110) and describe a 'Glaziale Serie' from 'Altmoräne' to 'Jüngere Deckenschotter' south of Memmingen or alternatively at the valley of the river Mindel. Two levels of 'Deckenschotter' had already been discerned by Penck (1899; see 3.2.4).

Current application.
The application of 'Mindel' in Bavaria corresponds largely with the original description. A period beginning with the decline of deciduous woodlands (not documented so far) subsequent to the 'Günz' and ending with the re-establishment of deciduous wood during the 'Mindel/Riß' is considered as 'Mindel'. However, west of the Iller Schreiner & Ebel (1981) verified an additional glacial period between 'Günz' and 'Mindel' called 'Haslach'. The associa-ted 'Haslachschotter' (Haslach gravel) was assigned to the 'Jüngere Deckenschotter' already by Penck & Brückner (1901–1909). 'Haslach'-equivalent deposits are supposed to exist also in Bavaria (Becker-Haumann 2005; Habbe et al. 2007) but so far this classification could not be clearly confirmed. The 'Haslach' of the type region is separated from the underlying 'Günz' by a fossil soil and by the superimposed interglacial of Unterpfauzenwald from the 'Mindel' (sensu stricto = classification system of Baden-Württemberg). Deposits of assumed 'Haslach' age in Bavaria may have been classified preferably as 'Mindel' so far. Hence the 'Haslach' in Bavaria is considered as an early subunit of 'Mindel' (sensu lato = Bavarian classification system) subdivided by at least one warm period (Unterpfauzenwald).

A further climate/chronostratigraphical unit 'Hoßkirch' was introduced by Ellwanger et al. (1995) into the classification system of Baden-Württemberg. It denotes the period of the lowermost Pleistocene basin deposits as shown by a drillhole at the basin of Hoßkirch, south to southwest of Saulgau. This new unit is documented palynologically as 'pre-Holsteinian'. At the same time 'Hoßkirch' is assumed to be younger than 'Mindel' because 'Mindel-aged 'Jüngere Deckenschotter' are situated in a higher position around the basin of Hoßkirch. For 'Hoßkirch' too, the occurrence of corresponding deposits is not yet verified in Bavaria and thus an integration in the climate stratigraphical classification of Bavaria would be premature. Deeply incised gravel deposits that are situated below the 'Ältere Hochterrasse' (see 3.2.6) may be assigned to a 'Hoßkirch' stage in the future.

Type region and occurrence.
The valley of the eponymous river Mindel lends itself as a type region for 'Mindel', almost literally in line with the descriptions of Penck & Brückner (1901–1909: 54). The moraines of the Holzheuer Höhe and the 'Oberegg-Saulengrainer Schotterzug' (string of gravel) demonstrate a classical 'Glaziale Serie' at the headwaters of the river Mindel. The gravel deposits merge with melt water channels of the same age near Mindelheim and continue as 'Kirchheim-Burgauer Schotter' along the Mindel-valley until reaching the Danube (Jerz et al. 1975; Löscher 1976; Becker-Haumann 2005: 218). The stratigraphical interpretation of the covering strata of the 'Kirchheim-Burgauer Schotter' in the brickyard-pit Offingen near the mouth of the river Mindel is still a matter of debate (cf. Rögner et al. 1988, Bibus 1995). However, the assignment of the underlying 'Jüngerer Deckenschotter' to the 'Mindel' is without controversy. Near Kirchdorf east of Mindelheim the 'Mindel'-aged Nagelfluh is overlain by 'Riß-glacial' till. The two units are separated by a fossil interglacial soil (Doppler 1993, Rögner 1993).

In search of a type region the area of the Rottal (Baden-Württemberg) has to be considered too. This particular area includes the type locality for the 'Haslach' glacial and the 'Haslachschotter, the 'Unterpfauzenwald interglacial' as well as the 'Tannheimer Schotter' ('Mindel' sensu stricto). Conditions are described in detail by Schreiner & Ebel (1981).

Depending on the stratigraphical interpretation of the uppermost till cover ('Mindel' after Rögner et al. 1988: 70, or 'Riß' after Roppelt 1988: 98) different parts of the section at the ravine of Hinterschmalholz near Obergünzburg may represent 'Mindel' (see 3.1.4).

'Mindel'-aged gravel deposits, in particular the 'Jüngere Deckenschotter' (see 3.2.5), are widespread in the rest of the Bavarian Alpine Foreland with exception of the Tertiary hills of Lower Bavaria. Furthermore, some of the most distal segments of the 'Altmoräne' from the former Iller glacier (disputed), partly from the Isar-Loisach glacier and from the Inn- and Salzach-glacier area are classified as 'Mindel'. The deeply incised Alpine valleys and glacier basins in the foreland contain isolated remnants of basin or moraine deposits which are regarded older than 'Riß' and are thus possibly of 'Mindel' age (Jerz 1979; Frank 1979). In the humid Alpine Foreland loess loam and other covering strata assigned to 'Mindel' are often masked by 'Pseudogley' sequences (stagnic cambisols or luvisols) which are hardly to differentiate (Brunnacker 1982; Bibus 1995).

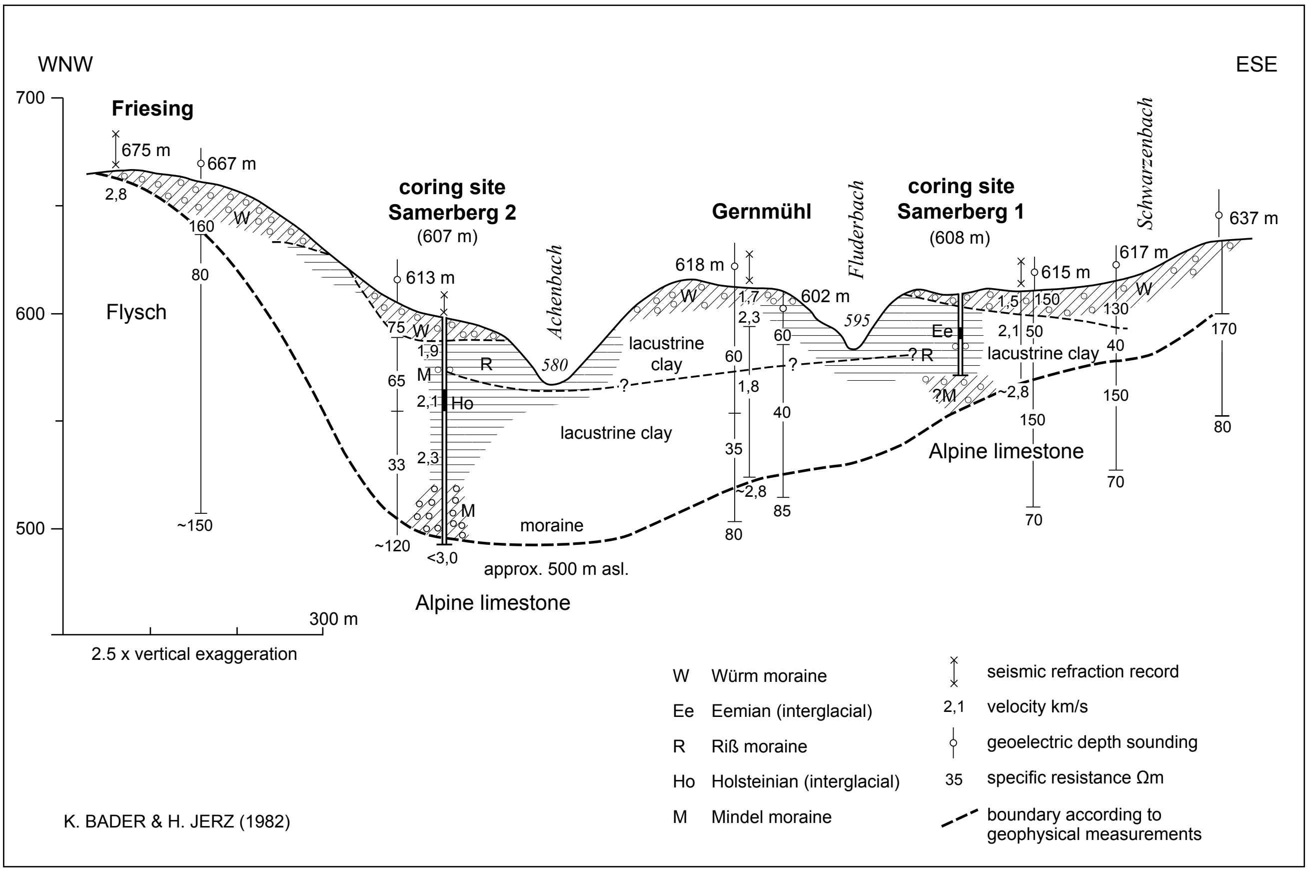


Fig. 4: Cross-section of the basin of Gernmühle (Samerberg) out of Rosenheim derived from geophysical measurements and the Samerberg research drillhole (from Jerz *1983).*

Abb. 4: Profilschnitt durch das Gernmühler Becken auf Basis geophysikalischer Messungen und den Samerberg-Forschungsbohrungen (aus Jerz *1983).*

Dating and references.

'Mindel' sensu lato probably has to be divided in two glacial phases, 'Haslach' and 'Mindel' sensu stricto. A reliable correlation with the MIS-curve for the whole extent is presently not possible. Probably only the upper termination can be linked to MIS 11 (or MIS 9?) by a correlation of 'Mindel/Riß' and 'Holsteinian'. This is in contrast to OSL-datings of sand layers in the 'Jüngere Deckenschotter' of the Mindel-valley near Offingen and Burgau which yielded ages of 260 ± 24 ka to 277 ± 24 ka (Klasen 2008). However, the results of the applied method were considered as unreliable by the author herself. TL-dating in Rögner et al. (1988) for a loess-like sediment sampled between overlying till deposits (not definitely classified as 'Mindel') and weathered loam in the ravine of Hinterschmalholz resulted in ages between 207 ± 27 ka and 278 ± 36 ka. A similar age of 278 ± 29 ka is obtained from the underlying flood deposit. Methodologically these ages have to be taken as minimum ages. The first surface-burial dating-approach applied to the 'Grönenbacher Schotter' (Häuselmann et al. 2007) yielded an age of 0.68 + 0.23/-0.24 Ma. This singular and first time age certainly needs affirmation by further dating analyses.

Single magnetostratigraphical investigations provided inconsistent results and implicate a miscorrelation between gravel beds east and west of the Iller, both classified as 'Mindel' (or 'Haslach-Mindel'). In the 'Jüngere Deckenschotter' at the vicinity of Pfullendorf in the Rhine-glacier area a reversed polarity was yielded (pers. commun. D. Ellwanger). On the other hand sand layers in the 'Jüngere Deckenschotter' in the Salzach-glacier area showed a normal polarity (Strattner & Rolf 1995; Doppler & Jerz 1995). According to these explanations the classification of 'Mindel' and correlations of suspected 'Mindel'-aged deposits may be considered as highly uncertain.

3.1.6 Mindel/Riß ('Mindel/Rissian')

First description and current application.

The warm period between 'Mindel' and 'Riß' is described as 'Mindel/Riß' interglacial by Penck & Brückner (1901–1909: 111). 'Mindel/Riß' is mainly represented by very thick weathered soils compared to the 'Riß/Würm' interglacial. Therefore Penck & Brückner (1901–1909) called the 'Mindel/Riß' phase 'Großes Interglazial' (major interglacial). The authors assumed a relatively long duration for this period. The current conception about the course and termination of the 'Riß' has changed the chronological but not the stratigraphical position of this warm period. It is assumed to correspond with the 'Holsteinian' of the Northern European classification. Likewise the Holsteinian 'Mindel/Riß' encompasses a period of deciduous forests characterised by the presence of wing nut and beech (*Pterocarya, Fagus*).

Type region and occurrence.

So far in the Northern Alpine Foreland occurrences of interglacial deposits between 'Mindel' and 'Riß' are found only very sporadically, for example at the site of the drillhole 'Samerberg 2' at the Bavarian Inn-glacier area (see Fig. 4; JERZ 1983; GRÜGER 1983), in the gravel pit 'Bittelschieß' at the Upper Swabian Rhine-glacier area (BLUDAU in ELLWANGER et al. 1999), and at the drillhole site 'Thalgut' in the Swiss canton Bern (WELTEN 1988; SCHLÜCHTER 1989). Neither underlying nor superimposed glacial deposits are dated so far and according to their basin position the interglacial deposits do not correspond with terrace systems. The classification of these sediments as Mindel/Riß therefore depends exclusively on palynological analogies with the 'Holsteinian' in the area of the Nordic glaciation. Although the pollen record of Samerberg shows an incomplete succession its overall picture fits well into the generally known sequence. Hence the Samerberg is currently regarded as 'Mindel/Riß type section for the German Alpine Foreland.

Another peat layer situated between a deeply incised gravel accumulation and overlying gravel deposits of the 'obere Hochterrasse' southeast of Regensburg, the so-called 'Hartinger Schichten' (Harting layers) is described by SCHELLMANN (1990). However, palynological investigations by GROSSE-BECKMANN (1993) gave no clear evidence for the (chrono)stratigraphical classification of the peat. Possibly the Hartinger Schichten even extend below deposits of the 'Jüngere Deckenschotter'. Thus, a correlation with 'Günz/Mindel' has to be given consideration too.

Other occurrences of 'Mindel/Riß' in the Bavarian Alpine Foreland are restricted to palaeosols developed on 'Mindel'-aged deposits. Loamy weathered gravel deposits have to be mentioned here, the 'Neufraer Boden' south of Riedlingen (BIBUS & KÖSEL 2001) or a palaeosol temporarily accessible at the construction site of the highway A96 east of Mindelheim (DOPPLER 1993, RÖGNER 1993). Mindel/Riß-aged soils often reach into the conglomerate host rocks by metres-long pipes. In other places parts of the lower layers of loess loam sections have to be assigned to 'Mindel'. In general these interglacial soils have transformed to 'Pseudogley' (stagnic cambisols or luvisols; DOPPLER & JERZ 1995).

Dating and references.
The correlation of the 'Mindel/Riß' interglacial of Samerberg and the 'Holsteinian' is based on the results of palynological investigations (GRÜGER 1983). The 'Holsteinian' in turn predominantly is thought to correspond with MIS 11 (approx. 420–360 ka). However, recently also a linkage to MIS 9 is suggested (e. g. GEYH & MÜLLER 2005). Numeric age determinations for the 'Mindel/Riß' interglacial are not available so far.

3.1.7 Riß ('Rissian')

First description.
The terms 'Riss' or Riss glacial are attributed to PENCK & BRÜCKNER (1901–1909: 110, 398). Penck applied it for the 'Glaziale Serie' from 'Altmoräne' to 'Hochterrassenschotter', which he observed along the Riß valley near Biberach. However, the connection between moraine ridges and melt-water terrace they assumed was later refuted (see 3.2.6). PENCK & BRÜCKNER (1901–1909: 31, Fig. 3, 4) were aware of different levels of the 'Hochterrasse' but nevertheless considered the 'Riß' as an undivided glacial unit.

Current application.
In accordance with the official spelling of the small eponymous river in Upper Swabia the climate stratigraphical unit most commonly is spelled 'Riß', only sometimes 'Riss'. The whole period between the decline of woodland after the 'Mindel/Riß Interglacial' ('Holsteinian 1' at Samerberg according to GRÜGER 1983; 'Pterocarya interglacial' after DRESCHER-SCHNEIDER 2001) and the beginning re-establishment of forests during the 'Riß/Würm-interglacial' is considered as 'Riß'. Meanwhile there is widespread evidence for a subdivision of the 'Riß' into different ice advances, as it is for the Saalian. 'Holsteinian 2' at Samerberg according to GRÜGER (1983) for instance correlates with the Wacken/Dömnitz interglacial, part of the Saalian 'complex' (LITT et al. 2007). However, a classification accepted by everyone and applicable to all 'Riß'-deposits is still lacking.

The subdivision of the 'Riß' is documented most explicitly at the type region selected by Penck – the Riß valley – as well as in other areas of the former Upper Swabian Rhine glacier (SCHREINER 1989; BIBUS & ELLWANGER 1995, MIARA 1996, BIBUS & KÖSEL 2001). A threefold subdivision into 'Älteres' ('Older Riß'; also 'Altriß', 'Zungenriß'), 'Mittleres' ('Middle Riß'; also 'Mittelriß', 'Hauptriß', 'Doppelwallriß') and 'Jüngeres Riß' ('Younger Riß'; also 'Jungriß') is assumed. The 'Obere Hochterrasse' (morphologically higher; for instance 21 m above the valley bottom of the river Riß) originates from the 'Doppelwall' (double ridge) and the 'Untere Hochterrasse' (morphologically lower; 13 m above the valley bottom of the river Riß) from a terminal moraine, which should be situated backward but is not clearly identifiable. 'Älteres Riß' is represented by till and gravel deposits below embankments of the 'Doppelwallriß' and possibly also by advanced moraine-ridges (SCHREINER 1989). According to BIBUS & KÖSEL (2001) it appears likely that all the three cold phases of the 'Riß' are separated by different palaeosols which indicate interglacial conditions (Tab. 2).

In Bavaria subdivisions of the 'Riß' are obvious too. They are documented by different moraine stages partly attributed to glacier oscillations or by different levels of the 'Hochterrasse'. However, these subdivisions are not formalised on a supraregional scale. Particularly in the Salzach-glacier area the subdivisions of the 'Riß'-aged moraines (GRIMM et al. 1979) seem comparable to those of the Rhine glacier. The 'Hochterrasse' in the Bavarian Alpine Foreland shows two terrace levels and an internal subdivision of the 'Obere Hochterrasse' (see 3.2.6).

Type region and occurrence.
The well-investigated Riß valley is regarded to be the type region, complemented by additional Upper Swabian sites (SCHREINER 1989 to BIBUS & KÖSEL 2001). 'Riß' is represented at many places in the Bavarian Alpine Foreland by tills and underlying gravel deposits of the ice-advance ('Vorstoßschotter'), while glaciofluvial terraces accompany most of the river valleys (cf. 3.2). Basin sediments and aeolian deposits on surfaces older than 'Riß' are to be mentioned too.

Dating and references.
'Riß' is positioned between the 'Mindel/Riß' interglacial (= Holsteinian of Samerberg) and the 'Riß/Würm' intergla-

cial (= Eemian). The latter is clearly identified at some locations in the Bavarian Alpine Foreland. 'Riß' probably correlates with the multi-phased Northern German 'Saalian' and thus encompasses the MIS 10 to MIS 6. So far no numeric dates of the intra-'Riß' warm phases are available because they are represented only by soil remnants. Tentatively they correlate with MIS 9 and MIS7.

At present only luminescence methods are available for numeric dating of deposits classified as 'Riß'. The few samples dated so far yielded ages of about 280 to 110 ka (Fiebig & Preusser 2003; Klasen 2008). The beginning and the termination of the 'Riß' is defined by the delimiting interglacials, which provide improved dating opportunities. Their correlation with MIS 11 and MIS 5e results in a time span between 360 and 128 ka for 'Riß'.

3.1.8 Riß/Würm ('Riss/Wuermian')

First description and current application.
Penck & Brückner (1901–1909: 111) use the term 'Riß/Würm' interglacial for the warm period between the 'Riß' and the 'Würm' glacials. They found it documented as a phase of incision into the older terrace deposits and in form of palaeosols. Besides this traditional perspective, the 'Riß/Würm' warm period can be classified biostratigraphically and by numeric ages nowadays. The 'Riß/Würm' interglacial encompasses the forested phase between 'Riß' and 'Würm'. Its climax stadium is characterised by increased portions of yew (Taxus). Frenzel (1978) assumed two different interglacials responsible for palynologically different types of 'Riß/Würm' interglacial occurrences in the Alpine Foreland ('type Zeifen' and 'type Pfefferbichl'). According to Drescher-Schneider (2000a) the difference is probably based on diverse forest communities depending on the altitudinal zone. So actually a 'Tieflandtyp' (lowland type) and a 'Alpiner Typ' (alpine type) may be discerned.

The correlation with the Eemian in the area of the Nordic glaciation is assured and this term is commonly used for the area of the Alpine glaciation too. However, the term 'Riß/Würm' is prefered here because it fits into the Alpine classification system and allows for possible variations due to different environments in both regions.

Type region and occurrence.
Due to its completeness and its diversification the most suitable type location of the 'Riß/Würm' interglacial is the profile of the lake sediments at Samerberg (Jerz 1979; Grüger 1979). The Mondsee section at the Salzkammergut/Austria (Drescher-Schneider 2009b) is regarded as comparably complete and even shows the succeeding development of the 'Early Würm'.

Further well-investigated but less complete sequences of 'Riß/Würm' deposits occur as lake marls or 'Schieferkohle' (compressed peat) at the following sites: Zeifen east of Lake Waging (Jung et al. 1972), Eurach south of Seeshaupt at the Starnberger See (former 'Würmsee'), Großweil east of Murnau, Herrnhausen south of Wolfratshausen, and Pfefferbichl near Buching (all mentioned in Bayerisches Geologisches Landesamt 1979, 1983). Another example of 'Riß/Würm'-aged deposits is the calcareous sinter ('Kalktuff') at the river Lech near Kolonie Hurlach north of Kaufering, which contains an interglacial mollusc fauna (Kovanda 1989).

The 'Riß/Würm' is also widespread in form of palaeosols, sometimes even called 'Eemboden' (Eemian soil). These palaeosols (e. g. 'Rosnaer Boden' after Bibus & Kösel 2001) occur on gravel deposits and moraines of the 'Riß' phase. The Riß/Würm soil is often the only well discernable interglacial soil in loess loam sections of the humid Alpine Foreland. Older palaeosols are difficult to distinguish because in most cases they are amalgamated to thick packets of Pseudogley (Stagnic Cambisol or Luvisol).

Dating and references.
The 'Riß/Würm' correlates palynologically and according to numeric ages with the Eemian of the Nordic classification system and therefore with MIS 5e. Palynological analyses on peats (in part called 'Schieferkohle') are mentioned above and in Table 1. It should be noted that also an interstadial origin has to be taken in account for some of the peat layers of the Alpine Foreland. Peat and the calcareous sinter of Hurlach are dated by the U/Th-method (Jerz 1993: 82; Jerz & Mangelsdorf 1989; Doppler 2003b). The results point to a period of formation between approximate 125 and 100 ka. So, in part the deposits are younger than the assumed duration of the 'Riß/Würm'-interglacial and their formation may have continued to the earliest parts of the 'Würm'.

3.1.9 Würm ('Wuermian')

First description.
The terms 'Würm', 'Würm glaciation' or 'Würm ice age' were introduced by Penck & Brückner (1901–1909: 110). Penck uses it for the 'Glaziale Serie' of the last glaciation that can be traced from the younger moraines of the Iller-glacier into the 'Memminger Tal'. In order to continue with his concept of naming glaciations in an alphabetical order he selected the Würm, a small river west of Munich which crosses the younger moraine ridges of the Lake Würm lobe (part of the Isar-Loisach glacier) and the adjacent Würm-aged alluvial plain of the 'Münchner Schotterebene'. Like the other glacials Penck & Brückner (1901–1909) considered the 'Würm' glacial as single-phase event. Thus their 'Glaziale Serie' primarily encompasses only the comparatively short pleniglacial period.

Current application.
Currently the whole period between the decline of woodlands after the 'Riß/Würm'Interglacial and their re-installation in the Holocene is considered as 'Würm'. Since the first definition by Penck & Brückner (1901–1909) different ideas emerged concerning the development and subdivision of the 'Würm'. This paper cannot refer to all of these conceptions.

Since 1983 the 'Würm' is subdivided formally into 'Unteres' (Lower), 'Mittleres' (Middle) and 'Oberes' (Upper) Würm' (Chaline & Jerz 1984). The 'Lower Würm' starts with the decline of woodlands after the 'Riß/Würm'-interglacial (pollen zone 13 in the Fluderbach section at Samerberg). It lasts until the end of the second interstadial of the 'Lower Würm' (pollen zone 25 of core Samerberg 1; Grüger 1979). The succeeding decline of trees (pollen zone

26) initiates the 'Middle Würm' whose end is defined as the lithological change of pelitic pond sediments to overlying gravel at the locality Baumkirchen at the Tirolean Inn valley. The gravel was deposited in front of the advancing Inn glacier ('Vorstoßschotter'). The 'Upper Würm' ranges to the Pleistocene/Holocene boundary as formally defined at a Greenland ice core (Walker et al. 2009).

In Bavaria, due to a lack of palynological data for most of the 'Würm' aged deposits, a pragmatic classification is applied. Instead of palynological features the last glacial advance into the Alpine Foreland is used as criterion for the division into 'Frühwürm' (Early Würm), 'Hochwürm' (Würm Pleniglacial) and 'Spätwürm' (Late Würm). 'Frühwürm' encompasses the whole period between the 'Riß/Würm' and the glacial advance of the 'Hochwürm'. The term 'Frühwürm' elsewhere – e. g. in Switzerland – however is used synonymic for 'Unteres Würm' ('Lower Würm'). The lower boundary of the 'Upper Würm' is conform to the 'Hochwürm'. However, concerning the gravel accumulations in front and below the advancing glaciers a clear separation of 'Early Würm' and 'pleniglacial' parts is mostly impossible like in the area of the former Loisach-glacier (Dreesbach 1986). According to the Bavarian classification all sediments of the 'Würm' deposited after the ice retreat from the 'Innere Jungendmoräne' (= internal terminal moraines of the Pleniglacial) are assigned to the 'Late Würm' (Chaline & Jerz 1984: 191). This corresponds only roughly with other definitions for the lower boundary of the 'Late Würm':

(i) by the retreat from younger ice margins like the 'Ammerseestadium' of the former Loisach glacier or

(ii) by palynological criteria. According to palynology glaciers had already retreated into the alpine valleys at the beginning of the 'Late glacial' (cf. Feldmann 1994: 234).

Type region and occurrence.

At the conference of the Subcommission of European Quaternary Stratigraphy (SEQS) in 1983 a type region of the 'Würm' was constituted in the area of the former Inn glacier including the localities Baumkirchen and Samerberg and the former Isar-Loisach glacier with its terminal moraine ridges around the Starnberger See or 'Würmsee' (Chaline & Jerz 1984). The 'Lower', 'Middle' and 'Upper Würm' are defined at the locations mentioned above.

The three units 'Frühwürm' (Early Wuerm), 'Hochwürm' (Pleniglacial) and 'Spätwürm' (Late Wuerm), especially the boundary between the latter units however are not defined at certain localities. Because of varying response times of glaciers to climate changes there may be minor differences concerning the chronology of different glacier lobes.

In the Bavarian Alps and the Bavarian Alpine Foreland deposits of the 'Würm' glacial are widespread and encompass different glacial remnants like glacio-lacustrine deposits in the deeply eroded alpine valleys and foreland basins and moraines of different characteristics. In the valleys melt-water deposits like 'Niederterrassen' and 'Spätglazialterrassen' but also 'Übergangsterrassen' (see 3.2.8, 3.2.9, 3.2.7) are classified to 'Würm'. Additional periglacial deposits of autochthonous valleys and other periglacial sediments have to be kept in mind, especially aeolian deposits like loess loam and loess to sand drift.

Dating and references.

The correlation of the 'Würm' with MIS 5d to 2 is beyond dispute and documented by numeric ages and palynological correlations. For the two older interstadials at Samerberg Grüger (1979) finds a correlation with the Brørup (MIS 5c) or the Odderade (MIS 5a) from the Nordic classification. With exception of an ambiguous third interstadial at Samerberg the sequence of MIS 4 to 3 is not yet resolved very well, even not in Baumkirchen.

However, plant remains derived from the varved clays at Baumkirchen were dated by radiocarbon. They document ice-free conditions in the Inn-valley until at least 25 ka BP. 27 ka BP is the youngest uncorrected radiocarbon age from the clay pit Baumkirchen, still several tens of metres below the front of proximal glacio-fluvial gravels (Fliri 1983, Patzelt & Resch 1986). The retreat from the 'Innere Jungendmoräne' and thus the beginning of the late glacial is not clearly defined. The Inn valley near Innsbruck was ice-free at around 14 ka BP, in accordance with first organic sedimentation in the Lanser See (Bortenschlager 1984). In the basin of the Murnauer Moos ice-free conditions are suggested from around 16 ka BP (Schneider 2006: 289). Thus the climatic conditions probably ameliorated clearly before 16 ka BP and brought about the ice retreat from the 'Innere Jungendmoräne'.

For a current classification of the Upper Pleistocene in Switzerland, based on luminescence and cosmogenic nuclide dating, see Preusser (2004) and Ivy-Ochs (2004).

3.1.10 Holocene

Superordinate chronostratigraphical units like Pleistocene and Holocene are defined internationally (Walker et al. 2008). The comment on the chronostratigraphical series Holocene thus may be restricted to regional aspects.

Current application.

So far a subdivision of the Holocene into subseries or stages (e. g. Bortenschlager 1982) is not formalised internationally. The sub-division of the Holocene used in Bavaria refers to the pollen record of Central Europe (Firbas 1949, 1952). 'Preboreal' and 'Boreal' (pre-warming period and early warming period) are summarised as Early Holocene and 'Atlantikum' and 'Subboreal' (warming period and late warming period) as Middle Holocene. The Late Holocene correlates with the 'Subatlantikum' (post-warming period).

Instead of the formal term 'Holocene' for the youngest still persisting episode in earth's history the name 'Postglazial' (Post Glacial) is often used in Bavaria, especially to name Holocene river terraces ('Postglazialterrassen'; see 3.2.10). The subdivision into early, middle and late Postglacial correlates with the classification into Early, Middle and Late Holocene, but there are no exact boundaries.

The Holocene encompasses the period of human settlement when men influenced significantly the ecosystem. Pollen grains e. g. of common hop/hemp (humulus/cannabis) in the Ammersee document the beginning of horticulture during the Boreal (Kleinmann 1995). At the river valleys human influence is traceable by wide-spread floodplain deposits ('Auenablagerungen'). Those fine-grained flood deposits are primarily attributed to outwash events in consequence of for-

Fig. 5: Schemes of terrace-flights of the Northern Alpine Foreland in Bavaria and partly Württemberg (without scale).

Abb. 5: Schematische Darstellung der Terrassentreppen des bayerischen (und württembergischen) Alpenvorlands (ohne Maßstab).

Fig. 5a: Proximal region (around Iller-Lech alluvial plain).

Abb. 5a: Proximaler Bereich (etwa Gebiet der Iller-Lech-Platte).

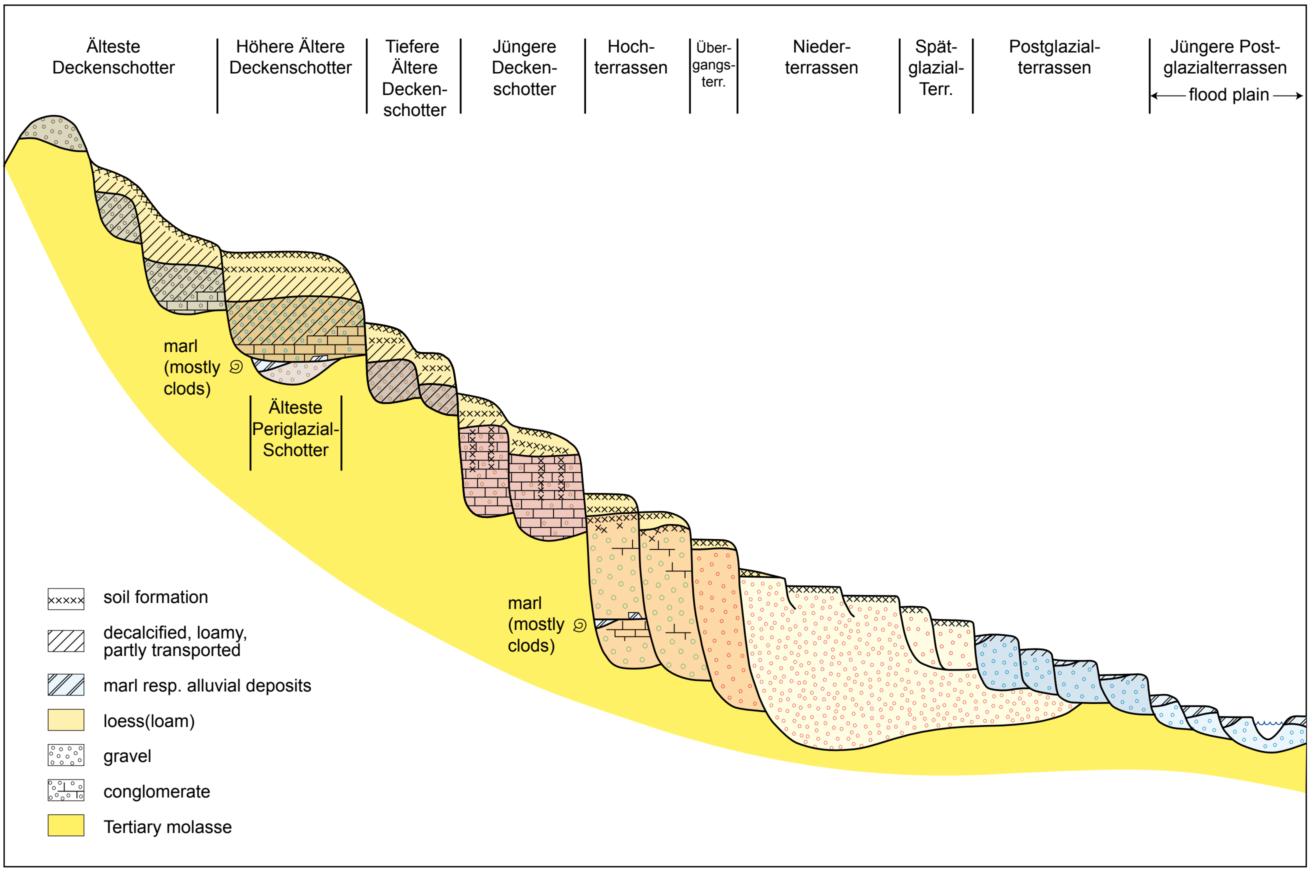
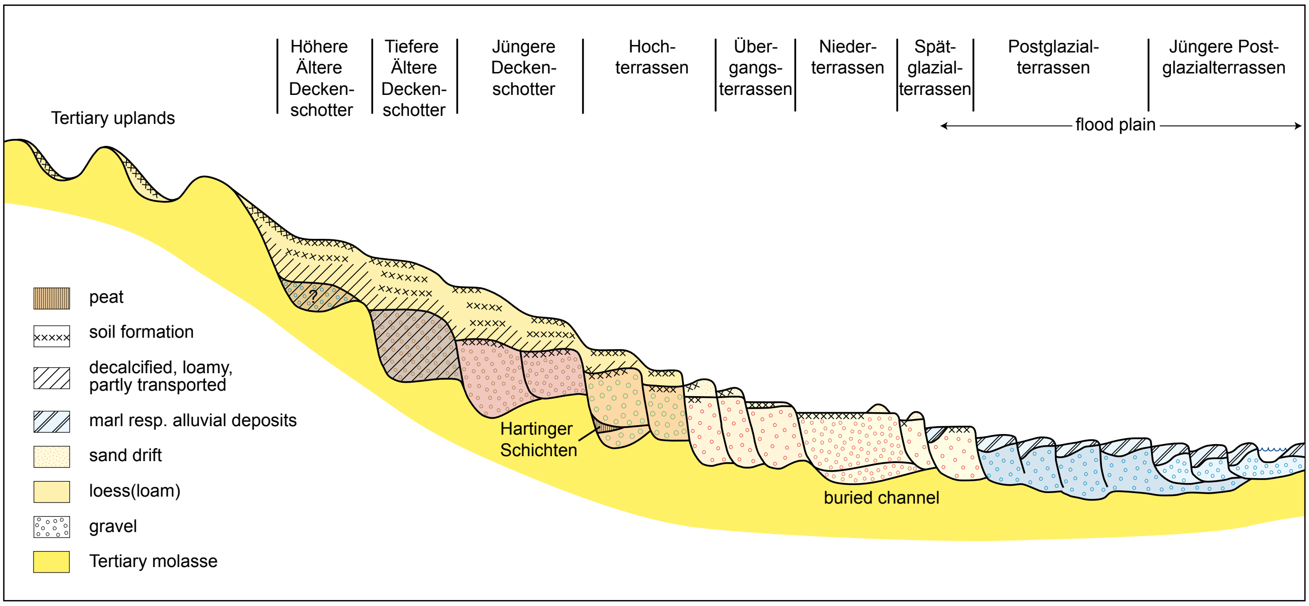


Fig. 5b: Distal region (around Dungau; changed after SCHELLMANN *et al. 2010: Fig. 19, 20).*

Abb. 5b: Distaler Bereich (etwa Dungau; verändert nach SCHELLMANN *et al. 2010: Abb. 19, 20).*



est clearing for the expanding agriculture since the Bronze Age (late Subboreal). Floodplain deposits – which are largely but not solely restricted to the Late Holocene – often display the only chronological subdivision of Holocene presented on geological maps apart from artificial accumulations. The early and the middle Postglacial are not clearly to distinguish without dating. River corrections and regulations primarily during the last 200 years brought an end to the natural dynamic of most of Bavaria's watercourses.

Occurrences.
In Bavaria Holocene deposits occur mainly as river sediments along most of the active watercourses. In addition Holocene lake deposits, peat bogs, calcareous sinter or redeposited material like aeolian drift sands, outwash-sediments and accumulations from mass movements can be discerned.

The geomorphodynamics during warm periods like the Holocene differ significantly from processes of the cold phases. Warm phases are characterised by a widely closed vegetation canopy, an active body of groundwater, and a resulting tempered run-off regime. Meandering rivers are documented by widespread terrace-sequences. At the lower reaches of the alpine rivers and in the Danube-valley terraces show only marginal differences in altitude ('Reihenterrassen' after Schirmer 1983). Sedimentological analyses combined with datings argue for a river dynamic which varied considerably during the Holocene. As the associated changes appear almost synchronously in all river systems of the Northern Alpine Foreland terrace development seems to be triggered by climatic changes.

Dating and references.
The Holocene encompasses the last 11.5 ka which is a comparatively short period with respect to the geological time scale. For classification or numeric age dating of Holocene deposits various methods exist depending on the material, like palynology, radiocarbon dating, luminescence dating, stable isotopes, dendro-chronology and archaeological and historic techniques. Thus, a high-resolution anatomy of this period is possible.

3.2 Terrace stratigraphy for Southern Bavaria

General information.
In Bavaria the terrace stratigraphy (classification by means of different terrace levels) applies the concept introduced by Penck (1882) and Penck & Brückner (1901–1909). In later years the terrace stratigraphical system was extended by Jerz et al. (1975) and Schellmann (1990) as is demonstrated in Table 4. Younger terrace deposits at the valleys are distinguished from older 'Deckenschotter' (approximately 'cover gravel') generally capturing the ridges between the valleys. However, in contrast to the original intention of the denomination it is not evident that 'Hoch-' and 'Niederterrassen' are restricted to valleys and 'Älteste' to 'Jüngere Deckenschotter' mainly occur as sheet-like deposits (see Fig. 5). The widespread 'Niederterrasse' of the alluvial plain of Munich ('Münchner Schotterebene') and the 'Jüngere Deckenschotter' of the Mindel-valley, which is delimited like a terrace, may be cited as examples (Penck 1899). The terms 'Hochterrasse' to 'Postglazialterrasse' are describing (geo)morphological forms after all. But at the same time they often are used for the associated sedimentary units (Schellmann 1990).

The terrace deposits of the Bavarian Alpine Foreland are predominantly composed of gravel with an Alpine provenance. Depending on the catchment area there are considerable variations especially concerning the ratio between carbonate and crystalline rocks. Gravel deposits of the same age may show a totally different composition. If the catchment of a glacier extends well into the Central Alps the amount of crystalline rocks generally increases towards the younger deposits. The absence of easily weathering dolomite and an enrichment of components resistant against weathering and transport are used for identification of periglacial gravels ('Liegendfazies' cf. Löscher 1976; 'Molassekristallinfazies' cf. Doppler 2003a). Fresh glacio-fluvial gravel deposits ('Hangendfazies' respectively 'Alpine Karbonatfazies') usually show nearly complete spectra of carbonaceous Alpine rocks, including dolomite. The river Danube along its course incorporates rocks of the Black Forest, the Alb region, and the eastern Bavarian crystalline basement. This enables an identification of former stream courses ('Urdonau' = proto-Danube cf. Scheuenpflug 1971; 'Weißjurafazies' cf. Löscher 1976).

Recent synopses of the gravel occurrences in the Bavarian Alpine Foreland including a detailed documentation of literature are provided by Doppler (2003), Rögner (2004), Becker-Haumann (2005) and Schellmann (2010). Some of the expansive interpretations of Becker-Haumann (2005) are not adopted here (e. g. concerning the origin of the 'Weißjuraschotter', the diversification of the 'Staudenplattenschotter' or of the 'Grönenbacher Feld').

3.2.1 Ältester Deckenschotter ('Oldest Cover Gravel')

First description.
For the first time the term Ältester Deckenschotter is applied probably by Jerz et al. (1975) as an extension of Penck's 'Deckenschotter' classification. The term denotes Pleistocene gravel deposits situated in the highest morphological positions of the Iller-Lech alluvial plain. However, Jerz assigns these accumulations partly to the 'Donau' glacial.

Current application.
The term is currently used by the Geological Survey in Bavaria for gravel deposits which correlate with terrace levels from the Staufenbergschotter down to the Staudenplattenschotter and are considered to be of 'Biber' age. This is in accordance with the reclassification of large parts of 'Ältere Deckenschotter' of the Iller-Mindel alluvial plain into the 'Donau' glacial by Löscher (1976). According to their altitude levels occurrences of the 'Älteste Deckenschotter' are described as 'Hochschotter', 'Oberer Deckschotter' and 'Mittlerer Deckschotter' by Graul (1949) and students as well as by Schaefer (1953). In contrast to Doppler & Jerz (1995) the 'Hochschotter' is summarised here too. Notwithstanding, in Baden-Württemberg the term is applied at the same time for 'Deckenschotter' of Donau age in the level of the 'Zusamplatte' (e. g. Erlenmooser and Erolzheimer Schotter).

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Tab. 4: Synopsis of terrace stratigraphical systems used in Southern Bavaria.

Tab. 4: Synopsis der Terrassen-stratigraphischen Nomenklatursysteme im deutschen Alpenvorland.

Climate-(Chrono-) stratigraphic classification BW = currently just in Baden-Wuerttemberg	Bavarian Environment Agency, based on: Penck & Brückner (1901-09), Jerz et al. (1976), Doppler & Jerz (1995)	Schellmann (1990): Lower Isar and Donau valley: 1 Geological Survey Baden-Wuerttemberg, Ellwanger & Villinger (2005): 2	Graul (1943 here also "Deckterrasse", 1962), Schaefer (1953), Löscher (1976), Tillmanns et al. (1983)	Schaefer (1953, 1955)	Eberl (1930)
Holocene	Postglazialterrasse(n)	Auenterrassen 1			
Late Würm	Spätglazialterrasse(n)				
Würm pleniglacial	Niederterrasse(n)	Niederterrassen 1+2	Niederterrassen	Niederterrassen	Niederterrassen
?Early Würm	Übergangsterrasse(n)	Übergangsterrassen 1			
Riß + Hoßkirch (BW)	Hochterrasse(n)	Hochterrassen 1+2	Hochterrassen	Hochterrassen	Hochterrassen
Mindel + Haslach (BW)	Jüngerer Deckenschotter	Jüngere Deckenschotter 1+2 Mittlere Deckenschotter 2	Zwischenterrassen	Zwischenterrassen	Altterrassen
Günz	Tieferer* Älterer Deckenschotter	Ältere Deckenschotter 1+2			Deckterrassen
Donau	Höherer* Älterer Deckenschotter	Älteste Deckenschotter 1+2	Unterer Deckschotter	Deckterrassen	'Donauschotter' + Ottobeurer Sch.
Biber	Ältester Deckenschotter + Älteste Periglazialschotter		Mittlerer Deckschotter Oberer Deckschotter	Höhenterrassen	
		Hochschotter 1	Hochschotter		

* "Tieferer" resp. "Höherer" in the sense of morphologically lower resp. higher (= younger resp. older)

Type region and occurrence.

The gravel deposits of the 'Staufenberg-Terrassentreppe' and the 'Staudenplatte' are suggested as type region for the 'Älteste Deckenschotter'. This unit has to be subdivided in probably at least three terrace-levels of different age: 'Höchste Älteste Deckenschotter' (= 'Hochschotter'; Highest Oldest Cover Gravel), 'Höhere Älteste Deckenschotter' (= 'Obere Deckschotter'; Higher Oldest Cover Gravel) and 'Tiefere Älteste Deckenschotter' (= 'Mittlere Deckschotter'; Lower Oldest Cover Gravel). Each of them needs an appropriate type locality.

The localities 'Hochfirst' on the Iller-Lech alluvial plain, 'Arlesrieder Schotter', 'Staudenplatte', 'Staufenberg-Terrassentreppe' and the 'Aindlinger Terrassentreppe' (flight of terraces) are counted among the occurrences of the 'Älteste Deckenschotter' in Bavaria. They all are attributed to the proto-Iller which extended in south-western to north-eastern direction to the present lower-end of the river Lech.

East of the mentioned occurrences on the Iller-Lech alluvial plain gravel accumulations indicating definitely an appropriate old age are so far not identified. Just along the former stream course of the Danube small elevated gravel deposits are described. A diversification from residual gravel deposits ('Restschotter') of the Miocene Upper Freshwater Molasse or possible Pliocene accumulations sometimes is difficult here because of complete weathering (e. g. Tillmanns 1977; Hilgart 1995).

Termination and lithology.

The 'Ältester Deckenschotter' displays the occurrence of glacio-fluvial gravel deposits most elevated in the Northern Alpine Foreland. Older gravel deposits are of Miocene (Upper Freshwater Molasse) or Pliocene origin. Their pebble composition is dominated by Quartz and thus they are to distinguish from fresh carbonaceous 'Ältester Deckenschotter'. The unit following the 'Älteste Deckenschotter' is the 'Höhere Ältere Deckenschotter' (Zusamplattenschotter and equivalents). Surface and base of this accumulations are situated more than 10 m lower than 'Älteste Deckenschotter'.

The 'Älteste Deckenschotter' is mostly decalcified and in general shows a completely weathered and partly loamy/silty residual gravel deposit. It is only rarely preserved as conglomerate. For the larger part the deposits are strongly dissected and affected by erosional processes. Mentionable covering strata of aeolian origin are just located at better preserved areas (e. g. near Markt Wald). But no section with a stratification according to the old age of these deposits has already been found.

Classification and correlation.

So far no direct numeric or relative datings of the 'Älteste Deckenschotter' are available. Only clods of marl in the 'Staudenplattenschotter' near Fischach and Walkertshofen (Eberl 1930: 309; Schröder & Dehm 1951) provided mollusc faunas which are comparable to the 'Bucher Schneckenmergel' (see 3.1.1). Based on its faunal composition a Tiglian age is probable for the 'Staudenplattenschotter'. Regarding the relationship with the 'Zusamplattenschotter' (see 3.2.3) the 'Staudenplattenschotter' may be assigned to an older part of Tiglian.

3.2.2 Ältester Periglazialschotter ('Oldest Periglacial Gravel')

First description and current application.

The term 'Ältester Periglazialschotter' is used by Doppler (2003) as collective name for gravel deposits which occur locally below the 'Höhere Ältere Deckenschotter'. The so-called 'Ottobeurer Schotter' (Eberl 1930), the 'Liegendfazies' (Sinn 1972; Löscher 1976), and the 'Urdonauschotter' (gravel of the proto-Danube; Scheuenpflug 1971, Villinger 2003) are considered as parts of this unit. The 'Älteste Periglazialschotter' are assumed to be deposited as channel fills aside of glacial runoff.

Type region and occurrence.

So far 'Älteste Periglazialschotter' are verified only in the western part of the Bavarian Alpine Foreland. The 'Ottobeurer Schotter' and the 'Liegend-' or 'Molassekristallin-Fazies' are to be found at the south-western Iller-Lech alluvial plain and the 'Zusamplatte', the 'Urdonauschotter' in the northern part of this area.

At present no permanent outcrops of the 'Ottobeurer Schotter' are available. Hence, we have to refer to the descriptions of Eberl (1930: 312), Sinn (1972) and Rögner & Löscher (1993). The 'Liegendfazies' or 'Molassekristallinfazies' in the Iller-Mindel alluvial plain may still be investigated in the vast clay pit near Altenstadt/Untereichen. From here these deposits are described on top of sandy Molasse sediments by Löscher (1976: 49). Another outcrop is the gravel pit west of Wettenhausen where superimposed glacio-fluvial 'Höherer Älterer Deckenschotter' could not be identified but may be masked by weathering.

The well-described gravel pit at the Kirchberg in Wörleschwang may serve as type locality of the 'Urdonauschotter' (Löscher 1976: 14; Becker-Haumann 2003: 158). The specific facies of the proto-Danube is exposed here temporarily in new gravel pits.

Termination and lithology.

The 'Ältester Periglazialschotter' mostly appears incised in sediments of the Upper Freshwater Molasse. The channel fill deposits are covered by 'Höhere Ältere Deckenschotter' in a facies dominated by Alpine carbonates. At some outcrops clods of marl are found at the base of this superimposed accumulation. Near Buch in-situ fine-grained flood deposits containing interglacial molluscs occurred in a comparable position (Schröder & Dehm 1951).

Due to a different pebble composition the 'Älteste Periglazialschotter' can be distinguished from the covering 'Höhere Ältere Deckenschotter'. The 'Ottobeurer Schotter' and the 'Liegendfazies' are characterised by a higher amount of central-alpine crystalline components. They are regarded as deposits of periglacial streams with a catchment area in the conglomerate sequences of the Miocene alluvial fan of the Adelegg (Sinn 1972; 'Molassekristallinfazies' cf. Doppler 2003a). The 'Urdonauschotter' in contrast is primarily composed of pebbles derived from the Alb (Malm limestone) and sporadically also from the Black Forest (e. g. red granite; Villinger 2003).

Classification and correlation.

Only the molluscs of the covering fluvial sediments, which are mostly preserved just as redeposited clods, enable a correlation with the Tiglian of north-western Europe (Rähle 1995; Münzing & Aktas 1984). Thus they give evidence for the minimum age of the underlying 'Älteste Periglazialschotter'. Generally just a relative classification older than the 'Donau'-aged covering 'Höhere Ältere Deckenschotter' is possible. Hence, a correlation with the 'Biber'-aged 'Älteste Deckenschotter' is feasible but not documented definitely. Apparently the 'Älteste Periglazialschotter' were deposited west of the 'Älteste Deckenschotter' of the proto-Iller and form the infill of a deeper incised discharge system.

3.2.3 Höherer Älterer Deckenschotter ('Higher Older Cover Gravel')

First description and current application.

The term 'Höherer Älterer Deckenschotter' is used for the first time by Doppler & Jerz (1995) describing the equivalents of the 'Zusamplattenschotter'. It is intended to distinguish an older part of the 'Älterer Deckenschotter' that occurs at a higher level in the type region near Memmingen from a younger part at a lower level. The first – called 'Höherer Älterer Deckenschotter' – is classified as 'Donau'-aged. The latter – called 'Tieferer Älterer Deckenschotter" – is assumed to be of 'Günz' age (see 3.2.4). Penck & Brückner (1901-1909) and in many cases also Eberl (1930) assumed a 'Günz' age for the total of all 'Ältere Deckenschotter'. Penck & Brückner (1901-1909) interpreted the higher position of some occurrences of their 'Ältere Deckenschotter' as a result of tectonic movements. Eberl (1930) disproved this view and introduced the new 'Donau' glacial to explain these circumstances (cf. 3.1.2).

In Baden-Württemberg deposits correlating with 'Zusamplattenschotter' are called 'Älteste Deckenschotter' like 'Biber'-aged gravels in Bavaria. Graul (1949) and his students (Sinn 1972, Löscher 1976) use the term 'Unterer Deckschotter' for corresponding deposits and assign them later on to 'Donau'.

Type region and occurrence.

The Zusamplatte – without the north-western extensions of the 'Druisheimer' and the 'Wortelstettener Schotter' – is suggested as type region for the 'Höhere Ältere Deckenschotter'. It should be made clear that the locally underlying 'Liegendfazies' respectively 'Molassekristallinfazies' (see 3.2.2) has to be separated from the 'Höherer Älterer Deckenschotter'. The gravel pits Altenstadt/Untereichen and Kirchberg at Wörleschwang may be regarded as type localities of the 'Höhere Ältere Deckenschotter' revealing especially its lower boundary to the underlying 'Älteste Periglazialschotter'.

More occurrences of the 'Höherer Älterer Deckenschotter' in the Riß-Lech alluvial plain can be traced from the region of Memmingen along the Zusamplattenschotter to the 'Untere Deckschotter' of the Aindlinger Terrassentreppe. All this gravel deposits originate from the proto-Iller (Sinn 1972). The isolated occurrence of the Stoffersberg near Landsberg/Lech may represent an affluent originating from the Lech area. In the eastern Bavarian Alpine Foreland further accumulations of 'Höhere Ältere Deckenschotter' occur along the former river course of the Danube (recent mapping of Schellmann) or along periglacial affluents (e. g. valley of the Paar, Doppler et al. 2002). They all show an elevated position above gravel deposits assumed to 'Günz'. Comparable evidence in the south-eastern Bavarian Alpine Foreland is still missing. Some gravel deposits on a higher level than 'Ältere Deckenschotter' but of assumed Pleistocene origin are described from the northern rim of the Hausruck and Kobernaußerwald (Upper Austria) in the foreland of the former Salzach glacier (e. g. 'Eichwaldschotter'; Ebers et al. 1966).

Termination and lithology.

'Höhere Ältere Deckenschotter' often are embedded more than 20 m deeper than the lowest 'Älteste Deckenschotter' ('Zusamplattenschotter' versus 'Staudenplattenschotter') and about 10 m higher than the bottom of the oldest accumulations attributed to the 'Tiefere Ältere Deckenschotter'.

The discovery of an interglacial mollusc fauna in the upper segment of the 'Zusamplattenschotter' near Lauterbrunn (Rähle 1995) implies that this widespread accumulation is probably composed of different sedimentary sequences of cold and warm phases of the 'Donau' age. However, no terrace flight is observable. That contradicts the view of Schaefer (1980) discerning an extensive number of terraces at the Zusamplatte. Moreover, it must be kept in mind that 'Älteste Periglazialschotter' and their covering fine-grained flood deposits (see 3.2.2) may occur not only below the 'Höhere Ältere Deckenschotter' but locally may reach to the surface.

Primarily in the southern areas where its remnants show a thickness of more than 5 m the 'Höherer Älterer Deckenschotter' is predominantly unweathered but in part contains brittle dolomite pebbles. A consolidation to Nagelfluh is possible and deep weathering cones may occur (e. g. 'Geologische Orgeln' at Bossarts south-west of Ottobeuren). The gravel distribution is less reduced by erosion than for 'Älteste Deckenschotter'. On widely preserved plateaus often covering strata of aeolian origin (loess loam) reach a thickness of more than 10 m. They are usually subdivided by surface-water gleyic palaeosols ('Pseudogley'). Below the last-interglacial soil these palaeosols are mostly amalgamated and do not approve a clear stratification.

Classification and correlation.

Biostratigraphical and magnetostratigraphical methods mostly can be applied in the covering strata (see 3.1.2; e. g. Uhlenberg) and result in minimum ages for the gravel deposits. Fauna is very rare, especially within the gravel deposits. The molluscs of Lauterbrunn are comparable with fauna collections from 'Älteste Deckenschotter' and other places of 'Höherer Älterer Deckenschotter' of the Iller-Lech alluvial plain. According to Rähle (1995) all these faunae correlate with the Tiglian.

Häuselmann et al. (2007) presented a first numeric age for the 'Höhere Ältere Deckenschotter' of the 'Böhener Feld' by cosmogenic nuclides (burial age dating). This method is in an early stage so that the resulting age of 2.35 +1.08/-0.88 Ma has to be considered with caution. 'Günz' age was originally supposed by Penck & Brückner (1901–1909) for the 'Böhener Feld' and adopted by Häuselmann et al. (2007). But since Löscher (1976) these conglomerates ('Nagelfluh') sampled at Wolfertschwenden are mostly assumed to be of 'Donau' age.

3.2.4 Tieferer Älterer Deckenschotter ('Lower Older Cover Gravel')

First description and current application.
Investigations by Penck (1899) at the Falkensporn (south of Memmingen) led to a disjunction of the 'Deckenschotter' in two autonomous accumulations separated chronologically into 'ältere' and 'jüngere' respectively 'obere' and 'untere Deckenschotter'. The 'Ältere Deckenschotter' he assigned to the fourth to last glacial called 'Günz'. Eberl (1930), Schaefer (1957), and Löscher (1976) carried out more detailed subdivisions of the 'Ältere Deckenschotter'. Only small parts of the formerly wide-spread gravel deposits remained to be of 'Günz' age. For these parts the term 'Tieferer Älterer Deckenschotter' was introduced by Doppler & Jerz (1995) in order to characterise the terrace morphological position between the 'Donau'-aged 'Höhere Ältere Deckenschotter' and the 'Mindel'-aged 'Jüngere Deckenschotter'. In the reverse conclusion 'Günz' is defined by the 'Tieferer Älterer Deckenschotter'. This is not satisfying but at that time without alternative.

Type region and occurrence.
Corresponding deposits are scarce on the southern Iller-Lech alluvial plain. Here for a trusted integration to the stratigraphic system a type location should be found for the 'Tiefere Ältere Deckenschotter'. Not until the north-western parts of the Iller-Lech alluvial plain they appear as 'Zwischenterrassenschotter' (Löscher 1976). But their classification into the 'Günz' by Doppler (2003a) as a continuation of the 'Zeiler Schotter' (Schreiner & Ebel 1981) is controversial. Löscher (1976) assigned the 'Zwischenterrassenschotter to the 'Donau'.

On the southern Iller-Lech alluvial plain the 'Tiefere Ältere Deckenschotter' is represented by some resticted occurrences of gravel deposits (Rögner 2004). However, their classification is not always undisputable. For instance recent mapping did not yield a difference of the 'Zadels-Stefansrieder Schotter' of assumed 'Günz' age and the 'Donau'-aged 'Böhener Schotter' (pers. commun. B. Lempe). One of the reasons for the limited distribution of 'Tiefere Ältere Deckenschotter' may be the reorientation in the main discharge direction of the glacial runoff of the former Rhine and Iller glacier. The flew direction moved from northeast during 'Biber' and 'Donau' near to north during the 'Günz'.

More outcrops of the 'Tieferer Älterer Deckenschotter' exist in the rest of the Alpine Foreland. They occur in the area of the 'Münchner Schotterebene' in a normal-stratigraphical succession below 'Mindel'-aged 'Jüngerer Deckenschotter' (e. g. 'Klettergarten Baierbrunn', Jerz 1993). According to their position they mostly are exposed just along deeply incised valleys like that of the Isar. In the foreland of the former Inn glacier they build up the 'Rattenkirchener Schotterfeld' (König 1979: 47). In the Bavarian part of the former Salzach-glacier foreland an occurrence at the Eschelberg west of Burghausen is to be mentioned (Eichler & Sinn 1974). At the Hechenberg more close to Burghausen and around Altenmarkt at the river Alz gravel deposits probably were accumulated during the advance of the 'Günz'-aged glacier (Doppler 1980: 152–159). It is not possible to correlate these basin internal occurrences directly with terrace stratigraphical units of the foreland. Also along the former river course of the Danube as well as in autochthonous tributaries like the valley of the Paar corresponding levels of gravel-bearing terraces are verified (Schellmann 1990; Doppler et al. 2002).

The 'Fagotienschotter' (named after the gastropod *Fagotia acicularis*) west of Moosburg between the valleys of Isar and Amper was deposited during a warm period as demonstrated by the included molluscs. The gravel deposits are situated on the level of the 'Hochterrasse' of the Isar but biostratigraphically they should be older than the Northern German 'Elsterian' according to Kovanda (2006). They may represent a warm phase during the deposition of the 'Tiefere Ältere Deckenschotter' or an interglacial gravel deposit of the 'Günz/Mindel' which so far was not regarded in the Bavarian Alpine Foreland.

Termination and lithology.
Compared to older deposits the base of the 'Tiefere Ältere Deckenschotter' on the Iller-Lech alluvial plain generally is more clearly incised. The base of the 'Höhere Ältere Deckenschotter' on the northern Iller-Lech alluvial plain is still located about 10 m higher. The base of the 'Jüngere Deckenschotter' is situated considerably about 20 m lower in the area of Ulm.

In contrast to the 'Höherer Älterer Deckenschotter' the 'Tieferer Älterer Deckenschotter' is not underlain by channel fills rich in crystalline Molasse pebbles. Generally, the 'Tiefere Ältere Deckenschotter' are characterised by a composition dominated by carbonate pebbles. Crystalline pebbles are hardly to find. In contrast to this in the area of the 'Zwischenterrassenschotter' in the northern Riß-Lech alluvial plain the deposits are typified by relic pebbles and the absence of carbonate material. It is not finally assured if this results form reworking of older weathered gravels (Löscher 1976) or in-situ weathering (Doppler 2003b). The periglacial gravel deposits of the Paar valley (Doppler et al. 2002), but also the glacio-fluvial gravel deposits of the Eschelberg west of Burghausen (Grimm et al. 1979) show completely aberrant spectra dominated by Quartz which is a result of reworking Molasse gravel.

Like all of the 'Deckenschotter' the 'Tiefere Ältere Deckenschotter' show calcitic conglomerations throughout the whole accumulations and not only near the valley rims. At some places the conglomerates ('Nagelfluh') are interspersed with partly very broad and deep weathering structures similar to the narrower geologic pipes of the 'Jüngere Deckenschotter' ('Geologische Orgeln'; e. g. 'Klettergarten Baierbrunn').

Classification and correlations.
So far the 'Tieferer Älterer Deckenschotter' is not dated by numeric or biostratigraphical methods. So, only the relative stratigraphical position can be determined based

on the terrace sequences and covering strata (e. g. Bibus 1995). A magnetostratigraphical analysis of fine-grained sediments in related moraine deposits (Bibus et al. 1996) or in loess loam strata was tried (Strattner & Rolf 1995; Doppler & Jerz 1995). The results are ambiguous. Reversed polarity is yielded for the moraine deposits and a normal polarity for loess strata of assumed similar age. Thus, these results are not sufficient to support extensive correlations to sequences outside the distributional area.

3.2.5 Jüngerer Deckenschotter ('Younger Cover Gravel')

First description and current application.
In the fundamental chapters and profiles of Penck & Brückner (1901–1909: 31, 48) the term 'Jüngerer Deckenschotter' or 'Unterer Deckenschotter' is applied for the Grönenbacher Feld near Memmingen. However 'Deckenschotter' are sub-divided already by Penck (1899). Additionally Penck & Brückner (1901–1909: 110) refer to equivalent terrace deposits along the Mindel valley and at the Rothwaldfeld northwest of Schongau.

So far in Bavaria the term 'Jüngerer Deckenschotter' is used to indicate gravel deposits of the 'Mindel' glacial. Compared to Penck & Brückner (1901–1909) only minor changes have been made by discerning accumulations of 'Jüngere Deckenschotter' with different age. An older gravel accumulation assigned as 'Haslachschotter' in the Upper Swabian Rot valley is separated from a younger ('Tannheimer Schotter' = 'Mindel' sensu stricto). The 'Haslachschotter' is eponymous to the Haslach glaciation (Schreiner & Ebel 1981; see 3.1.5).

Type regions and occurrences.
The type region for the 'Jüngere Deckenschotter' preferably has to be located in the Iller-Lech alluvial plain. Penck & Brückner (1901–1909: 28, 31, Fig. 3, 4) describe the Grönenbacher Feld as a typical occurrence of the 'Jüngere Deckenschotter'. An interglacial subdivision of this accumulation was recently suggested by Becker-Haumann (2005: 229) but is not widely accepted. Other references concern the valley of the river Mindel ('Kirchheim-Burgauer Schotter') where glacial runoff is documented from the 'Altmoräne' (older moraines) of the Holzheuer Höhe north of Obergünzburg down to the Danube (Penck & Brückner 1901–1909: 54, 110). The area of Upper Swabia will be of special importance for definition because of the clear subdivision of the 'Jüngere Deckenschotter' into two terrace deposits, the 'Haslachschotter' and the 'Tannheimer Schotter'. The two accumulations are separated by the soil remnants of a warm phase. On the other hand at the 'Klettergarten Baierbrunn' (climbing park) the 'Jüngere Deckenschotter' is embedded between gravel deposits of 'Günz' and 'Riß' age in a normal stratigraphical succession separated by relics of interglacial soils. However, a decision on formal type localities is not yet made.

'Jüngerer Deckenschotter' also frequently occurs in the Alpine Foreland apart from the areas already mentioned. A part of the 'Hochterrasse' in the Günz valley must be reckoned to the 'Jüngere Deckenschotter' based on the higher position of the gravel base and the habitus of the covering strata (unpubl. borehole data; Doppler 1985; Rögner et al. 1988; Bibus 1995). Further occurrences are found in the Rothwaldfeld northwest of Schongau between Wertach and Lech, in the northern Inn glacier foreland, and in the Dungau along the Danube southeast of Regensburg. Conglomerates crossing over in tills of assumed 'Mindel' age are known from most of the glacier lobes of Southern Bavaria and often are attributed to the 'Jüngere Deckenschotter'. Corresponding occurrences of gravel deposits of the ice-advance ('Vorstoßschotter') are widespread for instance at the Bavarian western flank of the Salzach glacier.

Morphologically many of the 'Jüngere Deckenschotter' can be coupled with parts of the 'Altmoräne' (older moraines) forming a 'Gaziale Serie'.

Termination and lithology.
Outside the moraine area the base of the 'Jüngerer Deckenschotter' is situated at about 10 m below the base of the 'Tieferer Älterer Deckenschotter' and more than 10 m above the base of the 'Riß'-aged 'Hochterrasse'.

Lithologically the 'Mindel'-aged 'Jüngerer Deckenschotter' generally is typified by a huge amount of carbonate pebbles of Alpine origin. However, it shows already an increasing content of crystalline components in the Rhine and Inn glacier area derived from their catchment area within the Central Alps. In contrast the Salzach glacier and the Isar-Loisach glacier, connected by transfluent pathways with the Central Alps too, show a significant increase of crystalline components at first during the 'Riß' glacial.

The 'Jüngerer Deckenschotter' is mostly conglomerated and shows intensive weathering structures at its surface. In some places 'Geologische Orgeln' (geologic pipes) could be found penetrating up to 10 m into the gravel deposits. These features often form spectacular narrow funnels (e. g. former quarry of Oberschroffen southeast of Altötting; see www.lfu.bayern.de/geologie/fachinformationen/geotope_schoensten/oberbayern/82). Partly these pipes are decapitated by erosion and contain either the original filling of weathered loamy gravel or the former residue has already flown out and the pipes are completely empty.

Classification and correlations.
According to the terrace stratigraphy the 'Jüngere Deckenschotter' have a relative position between the higher elevated 'Tiefere Ältere Deckenschotter' the lower situated 'Hochterrasse'. 'Jüngerer Deckenschotter' can be distinguished from 'Hochterrasse' sometimes by a lower content of crystalline pebbles, a higher degree of conglomeration, a more intensive weathering or the development of at least one more palaeosol in the covering strata. So far no fossils suitable for a biostratigraphical interpretation have been found. The few available magneto-stratigraphical data are inconsistent. Reversed polarity in the Rhine-glacier area near Heiligenberg close to Pfullendorf (pers. commun. D. Ellwanger) contradicts the normal polarity in the Salzach-glacier area near Trostberg (Strattner & Rolf 1995; Doppler & Jerz 1995).

Numeric datings were attempted by using cosmogenic nuclides or luminescence. A first burial-age for the 'Jüngerer Deckenschotter' of Bad Grönenbach by Häuselmann et al. (2007: 41) is given with 0.68 +0.23/-0.24 Ma. But as an output of a single measurement using a very new method this age seems not yet reliable. New IRSL-datings by Klasen (2008) are still inconsistent and will be currently reviewed.

3.2.6 Hochterrasse ('Higher Terrace')

First description.
In the valleys of the Alpine Foreland already Penck (1882: 254, 290) differentiated between a lastglacial 'unterer Glazialschotter' (lower glacial gravel deposit) without a loess cover and a higher elevated 'oberer Glazialschotter' (upper glacial gravel deposit) that generally is covered by loess. Penck (1882) used the term 'Hochterrasse' for the latter of both terrace levels and assigned its deposits later to the 'Glaziale Serie' of the 'Riß' (Penck & Brückner 1901–1909: 110). However, Penck supposed a nonexisting linkage between an older moraine stage ('Doppelwall' = double ridge) and a younger terrace ('Untere Hochterrasse' or '13 m-terrace'). Penck & Brückner (1901–1909) knew about different levels of 'Hochterrasse' – plains near Memmingen and in the Riß valley but did not apply a more detailed subdivision of these terraces.

Current application.
Recently a probably threefold subdivision of the 'Riß' separated by warm phases is assumed (MIS 10 to MIS 6; see 3.1.7). As a consequence variations of the covering strata and the degree of weathering on the different terrace levels led to a partly re-evaluation of diverse stages of the 'Hochterrasse' and their gravel deposits (Bibus & Kösel 1987, Miara 1996). In several valleys a lower (younger) and an upper (older) 'Hochterrasse' can be distinguished morphologically. In the Danube valley near Straubing three 'Hochterrasse' levels are described by Schellmann et al. (2010: 121). An even more extensive classification is carried out by Bibus & Strahl (2000) in the valley of the Danube near Höchstädt. They assign an 'Oberste (topmost) Hochterrasse' to the fifth last cold period. By the means of the stratigraphic classification applied in this paper this would be 'Mindel' and hence this highly elevated accumulation will be regarded as 'Jüngerer Deckenschotter'. The gravel deposits of the less elevated 'Obere Hochterrasse' locally are separated in two superimposed accumulations. This subdivision was found near Höchstädt too (Leger 1988; Bibus & Strahl 2000) and also in the Lech valley (Tillmanns et al. 1982; Aktas & Frechen 1991; Becker-Haumann & Frechen 1997). The two gravel accumulations in some places are separated by clods of marl at the base of the upper accumulation for once also a single pelitic layer in the intersection of both accumulations. These marls partly provide molluscs indicative for an interglacial interruption of the gravel deposition. At the valley of the Danube between Regensburg and Straubing the 'Obere Hochterrasse' but perhaps even the 'Jüngerer Deckenschotter' are underlain partly by gravel-bearing channel fills. At Regensburg-Harting this accumulation is covered by an interglacial peat (see 3.1.6; Hartinger Schichten after Schellmann 1990).

Type regions and occurrences.
Extensive investigations on gravel deposits, weathering and covering strata of the 'Hochterrasse' (Miara 1996, Bibus & Kösel 1997) and the linkage to the type region of the 'Riß' argue to assign the gravel pits in the valley of the Riß near Baltringen in Württemberg as type locality for 'Obere' and 'Untere Hochterrasse'. The subdivision of the gravel deposits of the 'Obere Hochterrasse' in two separated accumulations is well-described from the gravel pit north of Münster on the 'Rainer Hochterrasse' (Tillmanns et al. 1982). In a quarry west of Höchstädt on the 'Dillinger Hochterrasse' reworked clods of marl but also in-situ sand and silt lenses could be observed. They at least in part include warm-temperate molluscs (Leger 1988: 329; Fig. 71; Bibus & Strahl 2000). And even one of the currently accessible gravel pits near Bobingen may serve as type section after further investigations.

'Hochterrassen' are widespread also in the remaining Bavarian Alpine Foreland along the river valleys but also in already abandoned valleys. The following occurrences should be noted because of their differentiation or recent investigation:

(i) 'Hochterrassen' in the further stream course of the Danube between Neuburg and the Weltenburger Enge (Weltenburg gap; Fiebig & Preusser 2003) and between Regensburg and Vilshofen (Kroemer 2007; Schellmann 2010) which are separated into different levels. However, the classification of the lowest loess-covered terrace as 'Übergangsterrasse' (Transitional terrace) of 'Early Würm' age has to be taken into account here.

(ii) The different levels of the 'Hochterrasse' in the Salzach-glacier area (Grimm et al. 1979; Doppler 2003b) with a significant lower 'Hochterrasse'.

The special characteristics of the 'Münchner Schotterebene' providing a normal stratigraphic gravel succession may be attributed to a neotectonic subsidence southwest of the 'Landshut-Neuöttinger Abbruch' (Landshut-Neuötting fault). However, a similar superposition by younger gravel deposits near the front of the connected moraines occurs in other places too, for instance in the Salzach-glacier area (see below). The usual terrace flight successions occur not until the so-called 'terrace-crossings' downstream.

The 'Fagotienschotter' west of Moosburg situated between the valleys of Isar and Amper was assigned morphologically to the 'Hochterrasse'. But due to its mollusc content it seems to be significantly older (Kovanda 2006; see 3.2.4).

Termination and lithology.
The superposition of gravels of the 'Hochterrasse' by those of the 'Niederterrasse' or of the 'Jüngerer Deckenschotter' by gravels of the 'Hochterrasse' and the separation of the accumulations by remnants of fossil soils are very common in the 'Münchner Schotterebene' (fluvial plain of Munich). Similar conditions frequently occur in the area of the former Salzach glacier, for instance at the eastern riverside of the Salzach at Burghausen (Starnberger et al. 2008), south of Palling (Ebers et al. 1966) or near Haselreit/Kienberg. At all of these sites 'Riß'-aged 'Hochterrasse' gravels are overlain by 'Würm'-aged 'Niederterrasse' gravels and separated by palaeosol relics. On the other hand downstream the Alz near the village Mankham/Tacherting geological pipes in the 'Jüngerer Deckenschotter' are cut by 'Hochterrasse' deposits (Ebers et al. 1966; Doppler 2003b).

Apart from these conditions the base of the gravel deposits of the 'Hochterrasse' may be situated up to 10 m lower in comparison to the 'Jüngere Deckenschotter'. Even downstream in the valley of the Danube the terrace surfaces are situated at least a few meters higher than the 'Niederterrasse' or 'Übergangsterrasse'. However, as a result of extreme downcutting locally the base of the gravel deposits of the 'Hochterrasse' may occur below the base of younger accumulations.

The gravel deposits of the 'Hochterrasse' derived from melt water pathways connected with central Alpine glaciers (Rhine, Isar-Loisach, Inn-Chiemsee and Salzach glacier) often show a significantly higher amount of crystalline pebbles compared to the 'Jüngerer Deckenschotter'. A similar significant difference to the pebble content of the 'Niederterrasse' does not exist. Conglomeration is discontinuous but wide-spread and may be very intensive and enduring in marginal valley outcrops. In contrast to the 'Jüngerer Deckschotter' the 'Hochterrasse' deposits mostly show weathering cones smaller than 2 m instead of geological pipes. However, significantly deeper weathering pipes were recently described from the Hawanger Feld southwest of Memmingen (Lempe 2008).

Classification and correlations.
Except of the cases of superposition the gravel deposits of the 'Hochterrasse' according to the terrace stratigraphy are situated between the higher positioned 'Jüngere Deckenschotter' and the lower positioned 'Niederterrasse' (resp. 'Übergangsterrasse'). Differences in the extent of soil development and the amount of palaeosols in the covering strata are used by Bibus (1995), Miara (1996), and Bibus & Strahl (2000) to differentiate at least three accumulations of the 'Hochterrasse'.

There is a lack of finding places and even of appropriate fossil taxa for an accurate biostratigraphical classification. An exception may be the observed clods of marl and rarely occurring lenses of marl at the base of the younger accumulation of the upper 'Hochterrasse'. These marls contain partly interglacial and partly cold-phase molluscs (Leger 1988: 329; Tillmanns et al. 1992; Rähle 1994). However, the material is mostly reworked and displaced and therefore provides only a limiting age for the embedding gravel deposits. Rähle (1994) assigns the interglacial fauna found in the clods of marl at Bobingen south of Augsburg and at Münster south of Rain older than Eemian.

Luminescence methods are available for numeric datings. Sand layers intercalating with gravels which were classified as 'Hochterrasse' so far and covering strata were sampled. Fiebig & Preusser (2003) and Klasen (2008) yielded minimum ages of about 280 ka up to 60 ka. Thus parts of the accumulations of the 'Rainer', the 'Neuburger' and the 'Ingolstädter Hochterrasse' seem to reach to the 'Early Würm' and therefore would have to be considered as 'Übergangsterrassen'. But the results of different luminescence methods are not always consistent (Klasen 2008). As a consequence the Early Würm luminescence ages could not yet be evaluated generally for the classification of the lower stage of the 'Hochterrasse' as 'Übergangsterrasse' (Transitional terrace).

3.2.7 Übergangsterrasse ('Transitional Terrace')

First description.
The term 'Übergangsterrasse' leads back to Schellmann (1990) and was introduced for a loess-covered terrace with a level between the typical 'Hochterrasse' and 'Niederterrasse' in the valleys of the lower Isar and the adjacent Danube. It is not yet proved how far the 'loess-covered Niederterrasse' (Brunnacker 1953a) and the 'Tiefere' or 'Jüngere Hochterrasse' (Miara 1996; Doppler 2003b) have to be considered as 'Übergangsterrasse'.

Current application.
The term 'Übergangsterrasse' is currently used by the Geological Survey of Bavaria for terraces which are assigned to the 'Early Würm' ('Frühwürm') due to their terrace morphological position, their weathering status, the development of their covering strata, as well as recent luminescence datings. Schellmann (2010: 11) divides the 'Übergangsterrasse' in two parts. However, definition and application of this comparatively new terrace stratigraphical unit has to be elaborated in the future.

Type regions and occurrences.
The area of the confluence of the rivers Isar and Danube and the Danube valley between Straubing and Osterhofen may serve as type area for the 'Übergangsterrasse', the gravel pit west of the Natternberg between Stauffendorf and Fehmbach as type locality (Kroemer et al. 2007). In this region the first description was carried out and dating results are already available (Schellmann 1990, 2010). Furthermore, similar occurrences are outcropping upstream the Danube valley between Ingolstadt and Neuburg and maybe in the 'Hochterrasse' of Rain (Fiebig & Preusser 2003) if dating results will be confirmed.

Termination and lithology.
The gravel deposits of the 'Übergangsterrasse' may be distinguished from older gravel deposits of the 'Hochterrasse' and younger deposits of the 'Niederterrasse' by their morphological position, the missing weathering of the 'Riß/Würm' interglacial and by their reduced, only pleni- to late-glacial loess cover. The upper sections of the gravel deposits locally show a minor internal deformation (cryoturbation?) and reworked, transported, weathered pelitic material. The base of the covering pleniglacial loess is typified by laminae of sand ('sand-stripes'). Locally, the covering loess may be altered completely by the Late Glacial to Holocene soil formation that continues into the underlying gravel deposit.
The known thickness of the gravel deposits of the 'Übergangsterrasse' varies between 5 and 10 m. The 'Übergangsterrassen' are unconformably underlain by the Molasse and/or older Pleistocene deposits (mostly gravel of 'Riß'-age). The upper boundary to the covering strata (wash-out deposits or loess) is considered as hiatus too.

Classification and correlations.
The relative stratigraphical position of the 'Übergangsterrasse' is between the lowest 'Hochterrasse' and the highest 'Niederterrasse'. However, the actual position of the surface

is located closer to the 'Niederterrasse'. The assignment to the 'Frühwürm' ('Early Würm' = Lower and Middle Würm) is based on the absence of a 'Riß/Würm' soil formation as well as of covering strata of 'Early Würm' age.

First numeric OSL-datings of different occurrences which so far were assigned to the 'Hochterrasse' resulted in ages between 90 and 25 ka. A sand sheet in the gravels at the suggested type locality near Stauffendorf yielded ages of 36–30 and 23–19 ka at the base of the superimposed loess (Kroemer 2010). According to the OSL-datings of 70–90 ka by Fiebig & Preusser (2003) for the 'Neuburger' and parts of the 'Rainer Hochterrasse' as well as the 'Ingolstädter Hochterrasse' (accumulated by the 'Schutter-Danube') a future classification as 'Übergangsterrasse' seems likely. The change of the stream course of the 'Altmühl-Danube' firstly to the Schutter valley and following into the current Danube valley has to be rearranged from the end of the 'Riß' glacial into the 'Early Würm' in this case.

3.2.8 Niederterrasse ('Lower Terrace')

First description.
The term 'Niederterrasse' originates from Penck (1884: 39) and was formalised by Penck & Brückner (1901–1909: 28, 48). But already Penck (1882) discerned these terrace level (see 3.2.6). The term 'Niederterrasse' was first used to denominate the terrace gravel of the 'Memminger Trockental' (dry valley) deriving from the 'Jungendmoräne' (younger terminal moraine).

Current application.
The current use of the term 'Niederterrasse' has changed in part. Gravel beds formed by melt water of the 'Late Würm' are separated as 'Spätglazialterrasse' (Late Glacial Terrace), so that the term 'Niederterrasse' is limited to accumulations of the Würm Pleniglacial now. However, some authors (Schellmann 1990, Feldmann 1990) continue to use 'Niederterrasse' for all of the pleniglacial and late-glacial gravel deposits .

In the area proximal to the moraines a differentiation of the 'Niederterrasse' (*sensu stricto*) into several sub-units attributed to single moraine stands is possible:

(i) 'Niederterrasse 0' (advanced younger terminal moraine = super-maximal stand)
(ii) 'Niederterrasse 1' resp. 'Hauptniederterrasse' (external younger terminal moraine correlating with the Last Glacial Maximum (LGM)
(iii) 'Niederterrasse 2' (intermediate stand of the 'middle' younger terminal moraine)
(iv) 'Niederterrasse 3' (internal younger terminal moraine)

Type regions and occurrences.
As an original type location the 'Memminger Trockental' (Penck & Brückner 1901–1909) has to be mentioned. But a transfer to the Isar or Inn glacier foreland appears reasonable. Here a complete differentiation into sub-units associated with terminal moraine ridge systems is given and first datings are available (Feldmann 1994, 1998; Megies 2006).

Comparable gravel beds of the 'Niederterrasse' exist along all the rivers of the Alpine Foreland which drained melt water during the pleniglacial 'Würm'. Apart from the rivers Isar and Inn, the valley of the Lech contains an exceptionally well developed terrace sequence that has been investigated in detail (Schreiber 1985, currently mapped by Schellmann and students).

Termination and lithology.
The definition of the 'Niederterrasse' by the connection to pleniglacial moraine stages would actually require the discrimination of earlier underlying gravel deposits of the advancing glacier. However, the possibility of tracing the corresponding boundary along the melt water deposits into the glacier foreland is very limited (see Schreiber 1985; Dreesbach 1986). So the gravel beds of the advancing phase are just separated as long as a till cover of the same depositional cycle is obvious. Downstream from the outermost moraine stand these early melt water deposits are usually integrated to the 'Niederterrasse'.

Regarding this kind of sequence the lower boundary of the corresponding gravels is mostly developed as a clear hiatus to the underlying Molasse sediments. But particularly in the proximate glacier foreland a normal stratigraphical overlap on older Pleistocene sediments may also be observed (see 3.2.6).

The thickness of the deposits of the 'Niederterrasse' averages between a few and several tens of meters. In the areas of ice-proximal sandur plains accumulations may exceed 50 m or more. However a share in these thick accumulations by gravels of the ice-advance or even older deposits cannot always be excluded.

Due to the position at the surface the uppermost part of nearly all of the 'Niederterrassen' is affected by soil formation. However, locally the 'Niederterrassen' are overlain by younger sediments like aeolian drift sand, in rare cases also loess (c. f. 'Übergangsterrasse'), alluvial fans, colluvial soils, and swamp and bog-lime deposits ('Wiesenkalk', 'Alm').

The 'Niederterrasse' in former melt water valleys primarily consists of gravel deposits always containing variable amounts of carbonate pebbles. In contrast gravel accumulations corresponding to periglacial, autochthonous tributaries coeval with 'Niederterrasse' contain material from the local catchment areas. They are generally free of carbonate material. Typically the melt water deposits consist of gravel with a variable sand content. In a proximal position to the moraines higher percentages of boulders and silt may be observed but this material quickly decreases downstream. The gravel was deposited by braided rivers and shows vertical bar aggradation ('Vertikalschotter' *sensu* Schirmer 1983). Occasionally the gravel is covered by thin blankets (< 1 m) of fine-grained fluvial deposits. Near the valley rims some fine-grained sediment may occur as reworked material from nearby slopes.

Depending on the crystalline content brown earth (cambisol, 'Braunerde') or argilic brown earth (luvisol, lessivé, 'Parabraunerde') are developed on top of the 'Niederterrasse'. They may range from a few decimetres thickness up to 1 m. The soil formation penetrates the fresh gravel deposit just rudimentally with very short finger-like cones. At dry places the soils also may be red-coloured while at high water tables hydromorphic soils are formed, especially half-bog deposits (so-called 'Pechanmoor' after Brunnacker 1959; Kroemer 2010). Where ground water occurs as planar outlet peat and bog-lime have formed (e. g. Erdinger and Dachauer Moos).

Classification and correlations.
The identification of the 'Niederterrasse' in the sense of a 'Glaziale Serie' is based on the geomorphological connection to terminal moraine stages of the 'Würm pleniglacial' and on the relative terrace stratigraphical position between the loess-covered 'Hochterrasse' (or 'Übergangsterrasse') and the terraces of the Late Glacial.

Numeric ages between 25 and 17 ka BP for the deposits of the 'Niederterrasse' were determined using radiocarbon datings on mammoth tooth (Geyh & Schreiner 1984) as well as OSL-datings (Fiebig & Preusser 2003, Megies 2006). Maximum and minimum ages may be deduced from underlying and overlying sediments. For example the loess-covered 'Niederterrasse' on the eastern bank of the river Salzach (Austria) opposite of Burghausen (Traub & Jerz 1976; Starnberger et al. 2008) yielded radiocarbon and OSL ages for underlying loess strata of 21.7±0.25 ka BP (25.92–25.04 ka cal. BP) respectively 19.9–21.5 ka.

3.2.9 Spätglazialterrasse ('Late Glacial Terrace')

First description and current application.
Terms like 'spätglaziale Terrasse' (terrace of the late glacial) or 'spätglazialer Schotter' (gravel of the late glacial) are used yet in former publications (e. g. Koehne & Niklas 1916). But it is not clear who at what time formed the term 'Spätglazialterrasse'. It was used in diploma theses of the 1970s at the Munich University (summarised by Grimm et al. 1979) and finally documented in Jerz (1993). For the Geological Map of Bavaria the term 'Spätglazialterrasse' is applied for melt water and gravel deposits of the 'Spätwürm' (late Upper Würm) which is the period after the ice retreat from the internal terminal moraine (see 3.1.9). Other authors (Schellmann 1990, Feldmann 1990) call the corresponding terraces and their deposits still 'Niederterrasse'. Two different levels may be frequently distinguished: 'Spätglazialterrasse 1' and '2' (respectively 'NT2' and 'NT3' after Schellmann 1990).

Type regions and occurrences.
The Danube valley near Straubing where a widespread bisection of the 'Spätglazialterrasse' is confirmed by current datings (Schellmann 2010) may serve as a type region for the 'Spätglazialterrasse'. Deposits of the 'Spätglazialterrasse' also occur along further river courses of the Alpine Foreland like the valleys of the Inn downstream of Kiefersfelden (Megies 2006), the Lech (Schreiber 1985), the Isar between Freising and Deggendorf (Feldmann 1990, Schellmann 1990), and the Danube between Dillingen and Donauwörth (e. g. Kleinschnitz & Kroemer 2003) or from Regensburg to Pleinting (Schellmann 1990; Buch 1988).

Termination and lithology.
Where river courses changed after the 'Würm Pleniglacial' the base of the deposits of the 'Spätglazialterrasse' may be incised into Molasse sediments or accumulations older than 'Würm' forming a significant hiatus. But in most cases Late Glacial deposits follow directly on top of the gravels of the 'Niederterrasse' sometimes just identifiable by a basal concentration of coarse boulders. Inside the tongue basins of the glaciers and the Alpine valleys the gravels of the 'Spätglazialterrasse' are underlain also by glacial till or glacio-lacustrine sediment.

The gravels of the 'Spätglazialterrasse' do not differ significantly from the gravels of the 'Niederterrasse' of corresponding catchments. They mostly show also vertical bar aggradation ('Vertikalschotter' *sensu* Schirmer 1983). But locally first tendencies to meandering features are visible, for example at the mouth of the Isar (Kroemer et al. 2007). Usually the thickness of the gravels varies between a few and several meters while a maximum of more than 10 m is occasionally reached.

Extreme thickness of overbank sediments is observed in the Danube valley, upstream of the confluence with the Isar (Kroemer et al. 2007, Kroemer 2010). On top of the Late Glacial gravel up to 3 m thick silty flood deposits occur which are locally underlain by up to 3 m thick deposits of fine sand. Typical soils on the top of the 'Spätglazialterrasse' are brown earths or argilic brown earths ('Parabraunerde'). But the degree of development is reduced compared to the 'Niederterrasse' (generally < 0.6 m). The widespread occurrence of half-bog (so-called 'Pechanmoor') argues for at least temporary high water tables in many areas even after shifting of river courses and lowering of the river beds during the Holocene.

Separated by minor discontinuities the terrace deposits in part are covered by younger sediments like accumulations of alluvial fans, colluvial, and flood deposits. In contrast to the younger terrace the higher (older) level of the 'Spätglazialterrasse' (resp. 'NT2') may be covered by 'Flugsand' (drift sand). The lower (younger) level of the 'Spätglazialterrasse' was still in fluvial formation during the deposition of the drift sand in the final permafrost period of the Younger Dryas.

Classification and correlations.
Geomorphologically and due to their weathering status the 'Spätglazialterrasse' has to be classified between the youngest 'Niederterrasse' and oldest 'Postglazialterrasse'. A direct connection to late glacial terminal moraine ridges (from 'Stephanskirchener'- or 'Weilheimer Stand' to Egesen moraines, see Tab. 5) is rarely possible. The Late-glacial terrace formation is attributed rather to fluvial transformations than to sediment pulses caused by glacier activities. River-dynamic reactions are triggered by climate changes and the deglaciation of the glacier basins.

The 'Late Würm' and in consequence the 'Spätglazialterrassen' are defined after Chaline & Jerz (1984). A complete correlation to the 'Late Würm' according to palynological analyses (Firbas 1949, 1952) is not expected (see 3.1.9).

Numeric radiocarbon datings in the area near Straubing (Schellmann 2010: 28) assign the deposits of the 'Spätglazialterrasse 1' to the 'Älteste Dryas' (oldest Dryas) between 17 and 18 ka BP and some time before 14 ka BP. The time of the deposition of the 'Spätglazialterrasse 2' spans between 14.0 and approximately 10.2 ka BP (Schellmann 2010: 35) and thus has continued until the end of the Younger Dryas.

3.2.10 Postglazialterrasse ('Post Glacial Terrace')

First description and current application.
The first use of the term 'Postglazialterrasse' is in the dark like it was already told for the 'Spätglazialterrasse'. The term is used by Jerz & Schmidt-Kaler (1999) and is almost synchronously introduced into the General Legend of the GK25 of Bavaria. According to the attribution to Lower, Middle or Younger Holocene ('Alt-, Mittel- and Jungholozän') there is a differentiation in 'Ältere' (Older), 'Mittlere' (Middle) and 'Jüngere Postglazialterrasse' (Younger Postglacial Terrace). However, just the areas influenced by flooding events of the Late Holocene and their corresponding deposits can be separated clearly. Therefore in many cases it is necessary to merge the 'Ältere' and the 'Mittlere Postglazialterrasse' and distinguish this combination from the 'Jüngere Postglazialterrasse', the Late Holocene floodplain stages including corresponding fine-grained fluvial deposits. Some authors just take a consecutive numbering to label the different Holocene terraces. So the terraces of the Isar and the Danube are subdivided as 'Holozänterrasse 1' to '7' ('H1'-'H7') by Schellmann (1990) and Feldmann (1990).

Type regions and occurrences.
Well developed and detailed investigated successions of the 'Postglazialterrasse' are available at different river courses of the Alpine Foreland. Due to the comprehensive classification, partly based on numeric datings, the Isar valley is suggested as type region (Feldmann 1990, Schellmann 1990).

A comparable differentiation of the 'Postglazialterrasse' was recently dated by Megies (2006) at the lower river course of the Inn. Further detailed investigations were achieved lastly by Schreiber (1985) at the Lech, by Schellmann (1990), Buch (1988), Jerz & Schmidt-Kaler (1995, 1999), Kleinschnitz & Kroemer (2003) and by Kroemer et al. (2008) at different segments of the Danube. Knowledge is steadily increasing in the context of current geological mapping.

Termination and lithology.
Like the deposits of the 'Spätglazialterrasse' the gravels of the 'Postglazialterrasse' often are not incised to sediments of the Molasse. In many cases gravel deposits of the 'Niederterrasse' serve as substratum. The Holocene gravel beds with a clearly reduced thickness can be distinguished not only by a coarsening of the basal grain sizes but additionally by their different texture. Less frequently are typical warm-phase remnants and components of historic origin. 'Postglazialterrassen' predominantly evolved by reworking of older mostly 'Würm'-aged gravel and thus show only a minor modified composition.

The Holocene river accumulations were deposited in large parts by meandering rivers and show often a lateral bar aggradation ('Lateralschotter' *sensu* Schirmer 1983). Especially in the lower course of the rivers of the Northern Alpine Foreland or of the Danube hypsometrically less differentiated so-called in-line terraces ('Reihenterrassen' *sensu* Schirmer 1983) are formed. The single meander beds are divided into a central part predominantly composed of gravel and into the former river bed courses mostly filled with thick fine-grained sediment.

Also apart from these meander fills 'Postglazialterrassen' are frequently covered by fine-grained flood plain deposits of variable thickness. Due to generally high carbonate contents in the Northern Alpine Foreland they are often referred as 'Fluss-' or 'Auenmergel' (fluvial or floodplain marls). But for example on the gravels of the river Inn, which are very rich in crystalline components, the carbonate content of flood deposits is comparatively low. Overall the thickness of the Holocene river deposits (channel fill gravels and floodplain deposits) ranges from a few to several metres and rarely exceeds 10 m.

According to their relatively young age the deposits of the 'Postglazialterrasse' are covered only by accumulations like colluvium, bog lime or peat in exceptional cases. The surfaces of the terraces generally show minor soil formation. Even the older ones do not reach a stadium more developed than rendzina or pararendzina, the younger Holocene floodplain deposits not more than virgin soils. At high water tables also peat occurs ('Pechanmoor').

Classification and correlations.
The immature soils characterise the deposits of the 'Postglazialterrasse' as accumulations of the youngest section of earth history. Geomorphologically they occur directly below the youngest 'Würm'-aged terrace ('Spätglazialterrasse') and reach down to the present river courses.

The classification is carried out by using different methods. Minimum ages for the gravel accumulations result from palynological investigations preferably on covering organic strata, from artefacts, and other archaeological indications. Dateable human products like brick or pottery remains found within the gravels however provide maximum ages for the 'Jüngere Postglazialterrasse' (Younger Postglacial Terrace).

Numeric ages reaching from 11.5 ka cal. BP up to the present were determined on organic remains like wood or peat by using the radiocarbon method. Wood remains found in rivers of the Northern Alpine Foreland with sufficient amount of tree-ring structures can be analysed by the dendrochronological method which allows a chronology in a one-year-resolution for the whole Holocene (Kromer & Becker 1993). OSL-datings on sand grains of the Holocene gravel deposits were successfully performed too.

3.2.10.1 Jüngere Postglazialterrasse ('Younger Post Glacial Terrace')

Due to their special characteristics some supplementary descriptions for the deposits of the 'Jüngere Postglazialterrasse' are given. The 'Jüngere Postglazialterrasse' is situated in the area of river-flood events during late prehistoric and historic times. Predominantly these terraces developed before the realisation of regulating activities which started for the large part during the 19th century. 'Jüngere Postglazialterrassen' are generally characterised by 'Auenablagerungen' (fine-grained flood plain deposits). Their deposition was probably triggered by widespread forest clearing for agriculture and started already during the Bronze Age at the end of the Subboreal period. At the lower cours-

Tab. 5: Moraine stratigraphical terms used in Southern Bavaria ?↓ = stratigraphical position maybe older.

Tab. 5: Moränenstratigraphische Begriffe des deutschsprachigen Alpenraums.

Stratigraphical section	Terminal moraine stand				(resp. other moraine ridges)			
	General denominations	Rhine glacier	Iller glacier	Lech-Wertach glacier	Isar-Loisach and local glaciers: Ammersee lobe	Isar-Loisach and local glaciers: Würmsee/Wolfratsh. l.	Inn glacier	Salzach glacier
		Schreiner (1997) Keller & Krayss (2005)	Ellwanger (1980) Habbe (1988) Link & Preusser (2005)	Grottenthaler (2009) Rögner (1979)	Schneider (1995)	Grottenthaler (1980) Jerz (1987) Hirtlreiter (1992) Feldmann (1998)	Troll (1924) Maisch (1982) Grimm et al. (in prep.)	Ebers et al. (1966) Grimm et al. (1979)
Subatlantic	stand of 1850				1850		1850	
Atlantic+Subboreal	unknown				unknown		unknown	
Preboreal+Boreal	unknown				?↓Brunntal			
Younger Dryas	„Egesen"				Brünnl Höllentalanger ?↓Reintalanger		Egesen	
Allerød								
Older Dryas	unknown				unknown		unknown	
Bølling								
Oldest Dryas	„Daun"				Quellen Hinterklamm		Daun Clavadel/Senders	
	„Gschnitz"	Andeer			Mitterklamm Bodenlaine		Gschnitz/Steinach	
Middle Late Würm	unnamed	Weißbad-Koblach			Leutasch Kanker/Partnachklamm Loisachtal /Eschenlohe Uffing Polling	Schwaiganger	„Bühl" (just local-phenomenon)	
Early Late Würm	unnamed	Konstanz	Dietmannsried	Bernbeuren	Weilheim Tankenrain Pähl („Ammerseest.)	Schönrain-Eurach	Stephanskirchen	Laufen
Würm pleniglacial	Innere Jungendmoräne	Stein am Rhein	Luiblings Vockenthal Käsers	Haslach	Wessobrunn	Münsing/Icking	Ölkofen	Lanzing
	Mittlere Jungendmoräne	Dießenhofen	Eichholz Hörensberg	Tannenberg	Hofstetten/ St. Ottilien	Leutstetten/ Ebenhausen	Ebersberg	Radegund
	Äußere Jungendmoräne	Schaffhausen	Schwenden Ziegelberg Niederholz	Altenstadt Sachsenried S Kinsau	Pürsch-Wald Reichling/ Schöffelding	Karlsburg/Schäftlarn	Haag Kirchseeon Altdorf Rechtmehring	Nunreut
	Vorgeschob. JEM (Supermaximalst.)	Saulgau	unknown	unknown	Stoffen/Steinlach	Neufahrn	Aying/Pframmern	Unterweißen-kirchen
Middle Würm	unnamed	?Untersee	S Kempten?	unknown	unknown	unknown	unknown	unknown
Lower Würm	unnamed		unknown	unknown	unknown	unknown	unknown	unknown

Riß/Würm								
Upper Riß	unsecured	unsecured	unknown	Oberostendorf-Lengenfeld	unknown	unknown	unsecured	unknown (just terrace)
Main Riß	„Riß-Doppelwall"	Riß-Doppelwall	unnamed	Unterrammingen-Ludwigsberg	unnamed	unnamed	unnamed	Kirchweihdach Tyrlaching
Lower Riß	Altmoräne	(e. g. Aßmanns-hardter Tal)	unknown	unknown	unknown	unknown	unknown	Schmidstadt Racherting
Mindel/Riß								
Mindel	Altmoräne	(e. g. Laupertshsn.)	Holzheuer Höhe/ Brandholz-Manneberg	unknown	unnamed (e. g. Parsberg SW Puchheim)	unknown	unnamed (e. g. St. Wolfgang-Oberornau)	unnamed (e. g. Margarethenberger Rücken)
(Haslach/Mindel)								
(Haslach)	Altmoräne	(Rappenbachtobel)						
Günz	Altmoräne	(Heiligenberg)	unknown	unknown	unknown	unknown	unnamed (Glatzberg)	Siedelberg (Oö.)
Donau	unsecured	unknown	unknown	unsecured	unknown	unknown	unknown	unknown
Biber	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown

es of the rivers of the Alpine Foreland or at the Danube valley the terrace levels show only sparse hypsometric differentiation. So Late Holocene flood plain deposits reach far beyond the terraces of the Younger Holocene onto older terrace surfaces.

Concerning the 'Jüngere Postglazialterrasse' three generations are basically distinguished partly with further subdivisions (Jerz & Schmidt-Kaler 1999; Kleinschnitz & Kroemer 2003; Schellmann 2010). Their formation in most cases can be determined as Bronze to Roman period, mediaeval, and modern times. Numeric datings by using the radiocarbon method or dendrochronology yielded ages between 3 ka BP until present. Beside the above mentioned methods also relics of human occupation or reworked artificial matter like ceramics can be applied for the classification. Historical maps like the primal cadastral mapping of the Bavarian Land Surveying Office serve as documents for the unregulated status of the rivers.

3.3 Moraine stratigraphy for Southern Bavaria

A continuous independent moraine stratigraphy is currently not available for Bavaria. On the Geological Map of Bavaria moraine deposits are distinguished by a combination of climate stratigraphical and petrogenetical terms. In addition specific moraine terminologies are used for the stratigraphical differentiation of moraines:

(i) a rough subdivision into 'Altmoräne' and 'Jungmoräne' (older and younger moraines) predominantly according to their morphological appearance,
(ii) a detailed supraregional applicable classification by discrimination of standardised terminal moraine stages during the 'Würm' and – less differentiated – during the 'Riß',
(iii) different classifications just related to one single glacier lobe using local names of terminal moraine ridge systems from 'Riß' to 'Holocene'.

All these classifications are largely limited to morphological landforms. A differentiation of distinct till generations deposited in superposition by different glacier advances of one cold stage is only exceptionally possible. It may be assumed just locally in single outcrops or in drillholes, so in the Rhine-glacier area of Baden-Wuerttemberg (e. g. Schreiner 1996) or in the Bavarian Salzach-glacier area (Grimm et al. 1979: 111). In rare cases a fossil soil is passed on between superimposed moraine deposits supporting an interglacial hiatus.

3.3.1 Geomorphological moraine classification

A rough geomorphological classification of the moraine topography which enables an elementary stratigraphical relation follows the suggestion of Penck & Brückner (1901–1909: 125). They distinguish 'Jungmoräne' (younger moraine) characterised by a pronounced relief showing directly its glacigenous origin from 'Altmoräne' (older moraine) with more flattened and well smoothed forms. Enclosed hollow moulds (above all dead ice kettles) characteristic for the moraine topography of the last glacial epoch are rarely found in the area of the 'Altmoräne' for instance. This is due to periglacial processes, increasing periglacial loam covers and interglacial weathering. 'Altmoräne' of 'Riß', 'Mindel' and for once even 'Günz' age generally constitutes an outer belt around the 'Jungmoräne' (see Fig. 1).

3.3.2 Classification by terminal moraine stages

The classification based on terminal moraine stages (= 'stand'; 'stadium' is regarded to be chronologically) is based on the course of the moraine ridges, of peripheral melt water channels, and supplemented also by relictic dead ice features. Corresponding classifications essentially depend on the particular image of the shape of a glacier lobe, but are rarely supported by datings. For the well-preserved moraine stands of the Würm pleniglacial, the Late Würm and the Holocene a superordinate climate control is assumed. This is due to the uniformity of the terminal moraine sequences developed in the different glacier lobes of the Northern Alpine Foreland (e. g. Troll 1924). Thus, from the local classifications a supra-regional standardised classification was derived for the 'Würm pleniglacial' and rudimentary also for the 'Riß' (Tab. 5). For the older just sparsely preserved deposits of the 'Altmoräne' a corresponding subdivision is not feasible. The glaciers of the 'Late Würm' to Holocene, which retreated into the Alpine valleys are strongly affected by local factors, so that only a less reliable correlation is possible.

In his pioneering publication about the Inn-Chiemsee glacier Troll (1924) paid special attention to the recessional moraine stages ('Endmoränen-Stände') of the 'Würm'. His classification into the 'Kirchseeoner', the 'Ebersberger', the 'Ölkofener' and the 'Stephanskirchener Stadium' is still in use. External of the 'Kirchseeoner'-terminal moraine stage remains of an older, more extensive but still 'Würm'-aged glacier advance exist, called the stage of 'Aying-Pframmern'. Partly those terminal moraine stages are subdivided into single echelons ('Staffeln'), for example the 'Haager', 'Altdorfer' and 'Rechtmehringer Staffel' of the 'Kirchseeoner Stand' (Troll 1924) or the recently performed differentiation of an 'Alt'- and a 'Jung-Ebersberger Stadium' by Darga (2009). The exemplarily developed young moraine stages of the Inn glacier are considered as a kind of model-classification for all of Bavaria. Comparable local classifications exist for most of the Bavarian glacier-lobes (Tab. 5).

A very detailed classification from 'Würm' to Holocene terminal moraines is presented from the Ammersee and partly the Würmsee lobe of the Isar-Loisach glacier. Lastly Hirtlreiter (1992), Schneider (1995) and Feldmann (1998) documented a large number of terminal moraine stages which are still visible between the 'Äußere Jungendmoräne' and the present day's glacier relics at the Wetterstein mountains (Tab. 5).

Moraine classification from 'Würm' to Holocene. Terminal moraine stages of the early 'Würm' as they are verified in Switzerland (Preusser 2004) are not documented clearly in the Bavarian Alpine Foreland up to now. However Link & Preusser (2005) specified indirectly a piedmont glaciation approximately 60 ka ago (MIS 4) in the basin of Kempten at the area of the Iller glacier.

The correlation of the terminal moraine stages of the Pleni-, Late- and Post-glacial of the 'Würm' is predominantly tentative (Habbe 1988: 183, Fig. 4). Concerning the terminal moraine stages of the 'Würm' pleniglacial the supra-regional classification distinguishes an 'Äußere Jungendmoräne' (external younger terminal moraine; e. g. 'Kirchseeoner Stand' of the Inn-glacier), a 'Mittlere Jungendmoräne' (middle; e. g. 'Ebersberger Stand') and an 'Innere Jungendmoräne' (internal; e. g. 'Ölkofener Stand'). The conceptual discrimination of 'Äußere'- and 'Innere Jungendmoräne' was firstly performed by Schmidt (1911) in the Rhine-glacier area. The 'Äußere Jungendmoräne' marks the external 'Würm'-aged, largely continuous terminal moraine stage which is often shaped as a double-ridge. The 'Innere Jungendmoräne' mostly rests on the edge of the tongue basins. The origin of the 'Innere Jungendmoräne' by some authors is attributed to a glacier readvance after an oscillation of elusive amplitude. According to Ellwanger et al. (2003) a change of the glacial mechanics from a 'cold' to a 'warm based glacier' took place with this readvance and even the glacier basins should not have been excavated before.

The term 'Mittlere Jungendmoräne' was introduced into the Bavarian geological legend for the widespread ridge structures and ice-decay landforms between the 'Äußere' and 'Innere Jungendmoräne'. They are mostly displayed as an independent terminal moraine stage, even though terminal moraine ridges are not predominantly. External to the 'Äußere Jungendmoräne' locally further moraine hills of probably Würm-pleniglacial age occur. They are denominated as 'vorgeschobene Jungendmoräne' (advanced younger terminal moraine) respectively 'Super-' or 'Supramaximalstand' (e. g. 'Ayinger Stand' of the Inn glacier). The latter two terms were introduced in the Rhine-glacier area too by German & Mader (1976). The first is used in Bavaria (e. g. Troll 1924: 32, Fig. 2; Ebers et al. 1966: 121).

Just local denominations are available for the terminal moraine stages of the 'Late Würm' when the ice had retreated from the 'Innere Jungendmoräne' and for the Holocene terminal moraines. The closely investigated terminal moraine stages of the Inn glacier and its tributaries in Austria (Patzelt 1980; Maisch 1982) may still be used as a master classification for Bavaria too.

A mostly indistinct moraine stage during Late-glacial ice retreat – still attributed by some authors to the pleniglacial (see 3.1.9) – displays the 'Stephanskirchener Stand' of the Inn glacier (firstly mentioned by Troll 1924) as well as its equivalents at other glacier areas of the Alpine Foreland. This moraine stage generally crests the outer rim of the central glacier basins. A younger superordinate moraine stage during the ice retreat was already described by Penck & Brückner (1901–1909: Fig. 60) in the Inn valley as 'Bühl-Stadium'. Reitner (2007) however revealed that the corresponding landforms are to explain by local interactions of the Inn glacier with tributary glaciers in the area south of Kufstein/Austria. That means 'Bühl' is not a climate controlled stage comparable among different glacier areas. Further superordinate Late-glacial stages which are supposed to have a climatic trigger are those of 'Gschnitz', 'Daun' and 'Egesen'. The latter is commonly connected to the last climate deterioration of the 'Late Würm', the

'Younger Dryas'. For the previous terminal stages the correlation to definable cold phases during the Late glacial is not verified so far.

Holocene glacier stages in the catchment of the former Inn glacier are described from the Central Alps (Mayr & Heuberger 1968; Patzelt & Bortenschlager 1978; Maisch 1982). But a reliable correlation to the few Holocene glaciers of the northern side of the Bavarian Alps will hardly be possible. The same is also true for their recessional moraine stages of the 'Late Würm'. So far only local classifications concerning single glacier tongues are available (last mentioned in Hirtlreiter 1992). Only the outermost terminal moraines of the so-called 'Little Ice Age' (14th to mid-19th century), the stages of 1850, give better opportunities for reconstruction by using historical sources.

For a comparative classification and correlation of terminal moraine stages different methods are used. These are connections by shared melt water outflows, the general position in the morphological sequence of the glacier lobes or calculations of the snow line. The last one was applied particularly for the younger, inner-alpine stages.

So far numeric ages for moraine stratigraphical units are very rare. Moraines generally lack in organic material useable for radiocarbon datings. Age determinations on sparse mammoth teeth are restricted to the Rhine-glacier area outside of Bavaria. Data are summarized in Keller & Krayss (1998). The opportunities to detect buried or reworked wood remains in Holocene moraines are more promising. But this approach has its limitation as well. So the classification of the terminal moraine stages at the origin of the Loisach-glacier by Hirtlreiter (1992) is based exclusively on snow line calculations and cannot be supported by numeric ages. Applying the relative new dating method of boulders via cosmogenic isotopes one has to consider disruptions caused by the intensive human occupation in the Alpine Foreland. First results were presented by Reuther (2007) and Ivy-Ochs et al. (2008) for the area of the Isar-Loisach and the Inn piedmont glaciers. Exposition ages determined on large erratic boulders cover a broad period between 10.3 and 38.9 ka (Ivy-Ochs et al. 2008: 565).

Moraine classification of the 'Riß'.

A detailed classification into terminal moraine stages comparable to the 'Würm' and with the objective of supraregional relevance just exists for the 'Riß' age. According to the morphologically less concise circumstances this classification shows some major uncertainties and so far analogies are evident only between the areas of the Rhine and the Salzach glacier enframing the Bavarian Alpine Foreland. The classification of the Rhine glacier by its conceptional terms of 'Zungen-Riß' ('tongue Riß'), 'Doppelwall-Riß' ('double ridge Riß') and the moraines of the 'Jung-Riß' ('younger Riß') denotes for supra-regional applicability. However, terminal moraine stages of the 'Zungenriß' and also of the 'Jung-Riß' are not documented clearly (Schreiner 1989).

The characteristics of the terminal moraine stages of the 'Riß' in the Bavarian Western Salzach glacier lobe (Grimm et al. 1979) with its inarticulate, external terminal moraine stages, an internal well developed double ridge and a youngest terminal stage, which is not documented directly, are well comparable to the classification of the Rhine-glacier area. Yet in the adjacent Western Inn-glacier area the classification is less comparable (Grimm et al. in prep.).

For 'Altmoränen' in the remaining Bavaria correspondingly detailed classifications are not available.

4 Discussion and perspectives

The status of Quaternary Stratigraphy in the Alpine Foreland of Baden-Wuerttemberg and Bavaria is described by Fiebig et al. (in press), Habbe, Ellwanger & Becker-Haumann (2007) or in the stratigraphic chart of the Deutsche Stratigraphische Kommission (2002) and the accompanying comment by Litt et al. (2005). In addition to the textbooks of Jerz (1993), Ehlers (1996), Schreiner (1997), Benda (1995) for Southern Germany, van Husen (2000) and Piller et al. (2004) for Austria, Schlüchter & Kelly (2000) and Preusser (2010) for Switzerland may be consulted for an outline.

The traditional, primarily morphostratigraphical classification used in Bavaria is essentially defined by gravel deposits of different elevations. So far it is suitable especially in the glacial foreland. In contrast the new, substantially lithostratigraphical classification system established in Baden-Württemberg defines units confined by discontinuities (Ellwanger et al. 1995, 2003). This system is based on the analysis of the sequences within the glacial basins of the Rhine glacier. The new classification introduces the so-called 'Hoßkirch-Komplex' (see 3.1.5) for the period of an oldest glaciation and basin formation in the area of Lake Constance preceding the 'Riß' complex. The new concept considers tectonic movements as a reason for all of the 'Deckenschotter' accumulations, not former phases of piedmont glaciations.

Palaeomagnetical investigations in the northern Rhine-glacier foreland (Fromm 1994; Ellwanger et al. 1995; Bibus et al. 1996) and in the Bavarian Alpine Foreland (Strattner & Rolf 1995) resulted in a different chronological classification of ('Haslach'-)'Mindel' and 'Günz' and thus also for the related units. Whereas 'Haslach-Mindel' and as a result also 'Günz' in Baden-Wuerttemberg is magnetostratigraphically attributed to the reverse oriented Matuyama, in Bavaria 'Mindel' is completely established in the normal oriented Brunhes epoch. Solely 'Günz' in Bavaria is thought to reach from the Matuyama up to the Brunhes epoch passing the Lower to Middle Pleistocene transition. The reasons for this discrepancy are still open. Probably on both sides of the river Iller (approximately the border between Wuerttemberg and Bavaria) gravel deposits of different ages are assigned to the 'Jüngere Deckenschotter' ('Mindel-Haslach') or 'Tiefere Ältere Deckenschotter' ('Günz'). The gravels of Allschwil with its covering strata containing 5 interglacial soils are classified as 'Jüngere Deckenschotter' (Zollinger 1991). Thus, considerably older deposits may be regarded as 'Mindel' in the upper Rhine area, than in Bavaria where the cover of 'Jüngere Deckenschotter' is less differentiated. But it remains unclear so far where a boundary between the different classification systems can be fixed.

Both classification systems are presented side by side in Table 3. We passed on displaying the classification of the Austrian Quaternary adjacent to the East because it is similar to the Bavarian system.

An adaptation between the different classification systems seems absolutely essential but against the background of various approaches also complex and interminable. The enforcement of further age-determinations, the enhancement of dating methods and the consolidation of new techniques may display an objective help but will surely implicate the loss of well beloved ideas.

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5 References

Aguirre, E. & Pasini, G. (1985): The Pliocene-Pleistocene boundary. – Episodes, 8: 116–120; Beijing.

Ad-hoc-AG Geologie: Geologische Kartieranleitung – Fachliche Grundlagen. – http://www.tlug-jena.de/geoka/hauptseite.htm.

Aktas, A. & Frechen, M. (1991): Mittel- bis jungpleistozäne Sedimente der Hochterrasse in der nördlichen Iller-Lech-Platte. – Geologisches Institut der Universität zu Köln, Sonderveröffentlichungen, 82: 19–41; Köln.

Bayerisches Geologisches Landesamt [ed.] (1979): Interglaziale und Interstadiale des Pleistozäns im Bayerischen Alpenvorland (Teil I). – Geologica Bavarica, 80: 188 p.; München.

Bayerisches Geologisches Landesamt [ed.] (1983): Interglaziale und Interstadiale des Pleistozäns im Bayerischen Alpenvorland (Teil II). – Geologica Bavarica, 84: 213 p.; München.

Becker-Haumann, R. (2005): Anwendung der Geoinformatik für die hochauflösende 3D-Modellierung fluviatiler Terrassenkörper – Die prä-risszeitliche Chronologie und Paläogeographie des Illergletschergebietes, Bayerisches Alpenvorland. – 330 p., Stuttgart (Schweizerbart).

Becker-Haumann, R. & Frechen, M. (1997): Vergleichende Lumineszenz-Datierungen mit IRSL und TL am Deckschichtenprofil Bobingen/ Lechtal. – Zeitschrift geologischer Wissenschaften, 25: 617–633; Berlin.

Benda, L. [ed.]: Das Quartär Deutschlands. – 408 p.; Berlin, Stuttgart (Bornträger).

Beug, H.-J. (1976): Die spätglaziale und frühpostglaziale Vegetationsgeschichte im Gebiet des ehemaligen Rosenheimer Sees (Oberbayern). – Botanisches Jahrbuch für Systematik, 95 (3): 373–400; Stuttgart.

Beug, H.-J. (1979): Vegetationsgeschichtlich-pollenanalytische Untersuchungen am Riß/Würm-Interglazial von Eurach am Starnberger See/Obb. – Geologica Bavarica, 80: 91–106; München.

Bibus, E. (1974): Abtragungs- und Bodenbildungsphasen im Rißlöß. – Eiszeitalter u. Gegenwart, 25: 166–182; Öhringen/Württemberg.

Bibus, E. (1995): Äolische Deckschichten, Paläoböden und Mindestalter der Terrassen in der Iller-Lech-Platte. – Geologica Bavarica, 99: 135–164; München (Bayerisches Geologisches Landesamt).

Bibus, E., Bludau, W., Ellwanger, D., Fromm, K., Kösel, M. & Schreiner, A. (1996): On Pre-Würm glacial and interglacial deposits of the Rhine glacier (South German Alpine Foreland, Upper Swabia, Baden-Württemberg). – In: Turner, C. (ed.): The Early Middle Pleistocene in Europe: 195–204.

Bibus, E. & Ellwanger, D. (1995): Gravel pit Bittelschiess. Glacial deposits and fossil soils at the Höchsten. – In: Schirmer, W. (ed.): Quaternary field trips in Central Europe, 1: 468–470; München (Pfeil).

Bibus, E. & Kösel, M. (1997): Paläoböden und periglaziale Deckschichten im Rheingletschergebiet von Oberschwaben und ihre Bedeutung für Stratigraphie, Reliefentwicklung und Standort. – Tübinger Geowissenschaftliche Arbeiten, D3: 89 p.; Tübingen.

Bibus, E. & Kösel, M. (2001): Paläoböden von Neufra, Bittelschieß, Baltringen und Rosna. – unpublizierte Manuskripte der Arbeitsgemeinschaft Alpenvorlandquartär (AGAQ): 7 p.; Tübingen.

Bibus, E. & Strahl, M. (2000): Zur Gliederung und Altersstellung der bayerischen Hochterrassen nördlich des Donauriedes. – Zeitschrift für Geomorphologie, N. F., 44 (2): 211–232; Berlin, Stuttgart.

Bludau, W. (1995): Altpleistozäne Warmzeiten im Alpenvorland und im Oberrheingraben – Ein Beitrag der Palynologie zum 'Uhlenberg-Problem'. – Geologica Bavarica, 99: 119–134; München (Bayerisches Geologisches Landesamt).

Bortenschlager, S. (1982): Chronostratigraphic Subdivision of the Holocene in the Alps. – Striae, 16: 75–79; Uppsala.

Brunnacker, K. (1953a): Die bodenkundlichen Verhältnisse der würmeiszeitlichen Schotterfluren im Illergebiet. – Geologica Bavarica, 18: 113–130, München (Bayerisches Geologisches Landesamt).

Brunnacker, K. (1953b): Der würmeiszeitliche Löß in Südbayern. – Geologica Bavarica, 19: 58–265; München (Bayerisches Geologisches Landesamt).

Brunnacker, K. (1957): Die Geschichte der Böden im jüngeren Pleistozän in Bayern. – Geologica Bavarica, 34: 1–95; München (Bayerisches Geologisches Landesamt).

Brunnacker, K. (1959): Zur Kenntnis des Spät- und Postglazials in Bayern. – Geologica Bavarica, 43: 74–150, München.

Brunnacker, M. & Brunnacker, K. (1962): Weitere Funde pleistozäner Molluskenfaunen bei München. – Eiszeitalter und Gegenwart, 13: 129–137; Öhringen/Württemberg.

Brunnacker, K. (1982): Äolische Deckschichten und deren fossile Böden im Periglazialbereich Bayerns. – Geologisches Jahrbuch, F14: 15–25; Hannover.

Brunnacker, K. , Boenigk, W., Koci, A. & Tillmanns, W. (1976): Die Brunhes/Matuyama-Grenze am Rhein und an der Donau. – Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 151 (3): 358–378, Stuttgart.

Buch, M. W. (1988): Spätpleistozäne und holozäne fluviale Geomorphodynamik im Donautal zwischen Regensburg und Straubing. – Regensburger Geographische Schriften, 21: 197 p.; Regensburg.

Chaline, J. & Jerz, H. (1984): Arbeitsergebnisse der Subkommission für Europäische Quartärstratigraphie – Stratotypen des Würm-Glazials (Berichte der SEQS 6). – Eiszeitalter und Gegenwart, 34: 185–206; Hannover.

Crowhurst, S. J. (2002): Composite isotope sequence. – The Delphi Project (www.esc.cam.ac.uk/new/v10/research/institutes/godwin/body.html).

Darga, R. (2009): Auf den Spuren des Inn-Chiemsee-Gletschers – Übersicht. – Wanderungen in die Erdgeschichte, 26: 175 p.; München (Pfeil).

Dehm, R. (1979): Artenliste der altpleistozänen Molluskenfauna vom Uhlenberg bei Dinkelscherben. – Geologica Bavarica, 80: 123–125; München (Bayerisches Geologisches Landesamt).

Deutsche Stratigraphische Kommission [ed.] (2002): Stratigraphische Tabelle von Deutschland 2002. – Potsdam.

Doppler, G. (1980): Das Quartär im Raum Trostberg an der Alz im Vergleich mit dem nordwestlichen Altmoränengebiet des Salzachvorlandgletschers (Südostbayern). – Unpubl. Dissertation Universität München: 198 p.

Doppler, G. (1993): Quartär und Molasse in Böschungen der Autobahntrasse A 96 zwischen Ammersee und Mindeltal (Oberbayern, Schwaben). – Geologica Bavarica, 97: 147–154, München.

Doppler, G. (2003a): Zur Gliederung von Ältesten Periglazialschotter und Älteren Deckenschottern im Rot-Günz-Gebiet (Oberschwaben und Bayerisch Schwaben). – Zeitschrift der deutschen geologischen Gesellschaft, 154 (2/3): 255–286; Hannover.

Doppler, G. (2003b): Geologische Übersicht des westlichen pleistozänen Salzachvorlandgletschers und seines Vorlands (Oberbayern). – Tübinger Geowissenschaftliche Arbeiten, D 09: 25–46, Tübingen.

Doppler, G., Fiebig, M. & Meyer, R. K. F. (2002): Geowissenschaftliche Landesaufnahme in der Planungsregion 10 Ingolstadt; Erläuterungen zur Geologischen Karte 1:100 000. – 172 p., München (Bayerisches Geologisches Landesamt).

Doppler, G. & Jerz, H. (1995): Untersuchungen im Alt- und Ältestpleistozän des bayerischen Alpenvorlands – Geologische Grundlagen und stratigraphische Ergebnisse. Geologica Bavarica, 99: 7–53; München (Bayerisches Geologisches Landesamt).

Dreesbach, R. (1986): Zur Lithostratigraphie des Würmglazials im Gebiet des Isar-Loisach-Gletschers / Oberbayern. – Zeitschrift der deutschen geologischen Gesellschaft, 137: 553–572; Hannover.

Drescher-Schneider, R. (2000a): The Riss-Würm interglacial from West to East in the Alps: an overview of the vegetation succession and climate development. – Geologie en Mijnbouw/Netherlands, Journal of Geosciences, 79: 233–239.

Drescher-Schneider, R. (2000b): Die Vegetations- und Klimaentwicklung im Riss/Würm-Interglazial und im Früh- und Mittelwürm in der Umgebung von Mondsee – Ergebnisse der pollenanalytischen Untersuchungen. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12: 39–92; Wien.

Drescher-Schneider, R., Beug, H., Müller, H. & Knipping, M. (2001): Biostratigraphie. – unpubliziertes Manuskript der Arbeitsgemeinschaft Alpenvorlandquartär (AGAQ): 13 p.

Ebel, R. (1983): Die Lagerungsverhältnisse der Schieferkohlen zwischen der Ostrach und der Iller bei Sonthofen im Oberallgäu. (Mit einem paläontologischen Beitrag von Richard Dehm). – Geologica Bavarica, 84: 123–146; München (Bayerisches Geologisches Landesamt).

Eberl, B. (1930): Die Eiszeitenfolge im nördlichen Alpenvorlande – Ihr Ablauf, ihre Chronologie auf Grund der Aufnahmen des Lech- und Illergletschers. – 427 p.; Augsburg (Benno Filser).

Ebers, E., Weinberger, L. & Del-Negro, W. (1966): Der pleistozäne Salzachvorlandgletscher. – Veröffentlichungen der Gesellschaft für Bayerische Landeskunde, 19–22: 216 p.; München.

Ehlers, J. (1996): Quaternary and Glacial Geology. – 578 p., Chichester (Wiley).

Eichler, H. & Sinn, P. (1974): Zur Gliederung der Altmoränen im westlichen Salzachgletschergebiet. – Zeitschrift für Geomorphologie, N.F., 18: 132–158; Stuttgart.

Eichler, H. & Sinn, P. (1975) Zur Definition des Begriffs 'Mindel' im schwäbischen Alpenvorland. – Neues Jahrbuch für Geologie und Paläontologie, Monatshefte, 1975: 705–718; Stuttgart.

Ellwanger, D. (1980): Rückzugsphasen des würmzeitlichen Illergletschers. – Arbeiten aus dem Institut für Geologie und Paläontologie der Universität Stuttgart, N.F., 76: 93–126.

Ellwanger, D., Bibus, E., Bludau, W., Kösel, M. & Merkt, J. (1995): Baden-Württemberg. – In: Benda, L. (ed.): Das Quartär Deutschlands: 255–295.

Ellwanger, D., Fejfar, O. & von Koenigswald, W. (1994): Die biostratigraphische Aussage der Arvicolidenfauna vom Uhlenberg bei Dinkelscherben und ihre morpho- und lithostratigraphischen Konsequenzen. – Münchner Geowissenschaftliche Abhandlungen, A26: 173–191.

Ellwanger, D., Lämmermann-Barthel, J. & Neeb, I. (2003): Eine 'landschaftsübergreifende Lockergesteinsgliederung' vom Alpenrhein zum Oberrhein. – In: Schirmer, W. (ed.): Landschaftsgeschichte im Europäischen Rheinland. – GeoArchaeoRhein, 4: 81–124; Münster.

Feldmann, L. (1990): Jungquartäre Gletscher- und Flussgeschichte im Bereich der Münchner Schotterebene. – Dissertation Universität Düsseldorf: 355 p.; Düsseldorf.

Feldmann, L. (1994): Die Terrassen der Isar zwischen München und Freising – Zeitschrift der deutschen Geologischen Gesellschaft, 145: 233–248; Stuttgart.

Feldmann, L. (1998): Der würmzeitliche Isar-Loisachgletscher. – GeoArchaeoRhein, 2: 103–120; Münster.

Fiebig, M., Ellwanger, D. & Doppler, G. (in press): Pleistocene Glaciations of Southern Germany. – Developments in Quaternary Science, 15 (Elsevier).

Fiebig, M. & Preusser, F. (2003): Das Alter fluvialer Ablagerungen aus der Region Ingolstadt (Bayern) und ihre Bedeutung für die Eiszeitenchronologie des Alpenvorlandes. – Zeitschrift für Geomorphologie, N. F., 47 (4): 449–467; Stuttgart.

Fink, J. (1956): Zur Korrelation der Terrassen und Lösse in Österreich. – Eiszeitalter und Gegenwart, 7: 49–77; Öhringen/Württemberg.

Firbas, E. (1949): Allgemeine Waldgeschichte. – Spät- und nacheiszeitliche Waldgeschichte Mitteleuropas nördlich der Alpen, 1: 480 p.; Jena (Fischer).

Firbas, E. (1952): Waldgeschichte der einzelnen Landschaften. – Spät- und nacheiszeitliche Waldgeschichte Mitteleuropas nördlich der Alpen, 2: 256 p.; Jena (Fischer).

Fliri, F. (1983): Die Inntalterrasse von Gnadenwald und der Bänderton von Baumkirchen. – In: International Union of Quaternary Research – Stratigraphic Commission [ed.]: Führer zu den Exkursionen der Subkommission für Europäische Quartärstratigraphie vom 13. bis 20. September 1983 im Nördlichen Alpenvorland und im Nordalpengebiet (Bayern, Tirol, Salzburger Land, Oberösterreich): 77–81, München.

Frank, H. (1979): Glazial übertiefte Täler im Bereich des Isar-Loisach-Gletschers. – Eiszeitalter und Gegenwart, 29: 77–99; Hannover.

Frenzel, B. [ed.] (1976): Führer zur Exkursions-Tagung des IGCP-Projektes 73/1/24, 1976: 'Quaternary Glaciations in the Northern Hemisphere'. – 141 p.; Stuttgart-Hohenheim.

Frenzel, B. (1978): Das Interglazial vom Pfefferbichl bei Buching, Landkreis Füssen. – Führer zur Exkursionstagung des IGCP-Projektes 73/1/24 (1976): 181–184; Bonn-Bad Godesberg (DFG).

Frenzel, B. (1979): Entwurf einer Beschreibung der Typus-Regionen und Typus-Lokalitäten des Pleistozäns im Alpenvorland, als Diskussionsgrundlage für die Sitzung der Subkommission für Quartärstratigraphie in Hohenheim. – Unpubliziertes Manuskript: 22 p.; Hohenheim.

Frenzel, B. & Jochimsen, M. (1972): Die Schieferkohlen aus der Umgebung von Wasserburg/Inn. – In: Führer zu den Exkursionen der 16. wissenschaftlichen Tagung der Deutschen Quartärvereinigung: 73–75; Stuttgart-Hohenheim.

German, R. & Mader, M. (1976): Die Äußere Jungendmoräne bei Waldsee und das Riedtal. – Jahreshefte der Gesellschaft für Naturkunde in Württemberg, 131: 39–49; Stuttgart.

Geyh, M. A. & Müller, H. (2005): Numerical ^{230}Th/U dating and a palynological review of the Holsteinian/Hoxnian Interglacial. – Quaternary Science Reviews, 24 (16–17): 1861–1872.

Geyh, M. A. & Schreiner, A. (1984): ^{14}C-Datierungen an Knochen- und Stoßzahn-Fragmenten aus würmeiszeitlichen Ablagerungen im westlichen Rheingletschergebiet (Baden-Württemberg). – Eiszeitalter und Gegenwart, 34: 155–161; Hannover.

Gibbard, Ph. L., Head, M. J., Walker, M. J. C. & Subcommission on Quaternary Stratigraphy (2009): Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. – Journal of Quaternary Science, 25 (2): 96–102.

Grafenstein, U. von, Erlenkeuser, H., Müller, J. & Kleinmann-Eisenmann, A. (1992): Oxygen Isotope Records of Benthic Ostracods in Bavarian Lake Sediments. – Naturwissenschaften, 79: 145–152; Berlin (Springer).

Graul, H. (1949): Zur Gliederung des Altdiluviums zwischen Wertach-Lech und Flossach-Mindel. – Berichte der Naturforschenden Gesellschaft Augsburg, 2: 3–31; Augsburg.

Grimm, W.-D., Bläsig, H., Doppler, G., Fakhrai, M., Goroncek, K., Hintermaier, G., Just, J., Kiechle, W., Lobinger, W. H., Ludewig, H., Muzavor, S., Pakzad, M., Schwarz, U. & Sidiropoulos, Th. (1979): Quartärgeologische Untersuchungen im Nordwestteil des Salzach-Vorlandgletschers (Oberbayern). – In: Schlüchter, Ch. (ed.): Moraines and Varves – Origin, Genesis, Classification: 101–119; Rotterdam (Balkema).

Grimm, W.-D., Wierer, J. F. & Hintermaier-Erhard, G. (in Vorber.): Erläuterungen zur Geologischen Übersichtskarte des nördlichen Inn-Chiemsee- und des nordwestlichen Salzachgletschergebiets. – Unpubl. Manuskript; München (Bayerisches Landesamt für Umwelt).

Grosse-Beckmann, D. (1993): Die Vegetationsentwicklung Süddeutschlands im Alt- und Mittelpleistozän auf der Grundlage pollenanalytischer Untersuchungen. – unveröff. Staatsexamensarbeit Universität Düsseldorf: 119 p.; Düsseldorf.

Grottenthaler, W. (1980): Erläuterungen zur Geologischen Karte von Bayern 1:25 000, Blatt Nr. 7833 Fürstenfeldbruck. – 82 p.; München (Bayerisches Geologisches Landesamt).

Grottenthaler, W. (2009): Geologische Karte von Bayern 1:25 000; Erläuterungen zum Blatt 8131 Schongau. – 54 p.; Augsburg (Bayerisches Landesamt für Umwelt).

Grüger, E. (1979): Die Seeablagerungen vom Samerberg/Obb. und ihre Stellung im Jungpleistozän. – Eiszeitalter und Gegenwart, 29: 23–34; Hannover.

Grüger, E. (1983): Untersuchungen zur Gliederung und Vegetationsgeschichte des Mittelpleistozäns am Samerberg in Oberbayern. – Geologica Bavarica, 84: 21–40; München (Bayerisches Geologisches Landesamt).

Habbe, K. A. (1986): Bemerkungen zum Altpleistozän des Illergletscher-Gebietes. – Eiszeitalter und Gegenwart, 36: 121–134; Hannover.

Habbe, K. A. (1988): Was kann eine geomorphologische Vollkartierung für die Stratigraphie des Quartärs leisten? – Berliner Geographische Abhandlungen, 47: 177–196; Berlin.

Habbe, K. A. (1989): Die pleistozänen Vergletscherungen des süddeutschen Alpenvorlandes – ein Resümee. – Mitteilungen der Geographischen Gesellschaft München, 74: 27–51; München.

Habbe, K.-A., Ellwanger, D. & Becker-HAumann, R. (2007): Stratigraphische Begriffe für das Quartär des süddeutschen Alpenvorlands. – Quaternary Science Journal, 56 (1/2): 66–83, Hannover.

Häuselmann, Ph., Fiebig, M., Kubik, P. W. & Adrian, H. (2007): A first attempt to date the original 'Deckenschotter' of Penck and Brückner with cosmogenic nuclides. – Quaternary International, 164/165: 33–42.

Hambach, U., Rolf, Ch. & Schnepp, E. (2008): Magnetic dating of Quaternary sediments, volcanites and archaeological materials: an overview. – Eiszeitalter und Gegenwart, 57 (1–2): 25–51; Hannover.

Hilgart, M. (1995): Die geomorphologische Entwicklung des Altmühl- und Donautales im Raum Dietfurt-Kelheim-Regensburg im jüngeren Quartär. – Forschungen zur deutschen Landeskunde, 242: 333 p.; Trier.

Hirtlreiter, G. (1992): Spät- und postglaziale Gletscherschwankungen im Wettersteingebirge und seiner Umgebung. – Münchner Geographische Abhandlungen, Reihe B, 15: 154 p.; München.

Höfle, C. & Müller, H. (1983): Interglaziale und interstadiale Stauseeablagerungen bei Steingaden im Ammergebirgsvorland. – Geologica Bavarica, 84: 147–152; München (Bayerisches Geologisches Landesamt).

Ivy-Ochs, S., Schäfer, J., Kubik, P. W., Synal, H.-A. & Schlüchter, C. (2004): Timing of Deglaciation on the northern alpine Foreland (Switzerland). – Eclogae geologicae Helvetiae, 97: 47–55; Basel.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P. W. & Schlüchter, Ch. (2008): Chronology of the last glacial cycle in the European Alps. In: Journal of Quaternary Science, 23: 559–573.

Jerz, H. (1979): Die quartären Ablagerungen im übertieften Wolfratshausener Zungenbecken (Oberbayern). – In: Schlüchter, Ch. (ed.): Moraines and Varves: 257–260; Rotterdam (Balkema).

Jerz, H. (1982): Paläoböden in Südbayern (Alpenvorland und Alpen). – Geologisches Jahrbuch, F14: 27–43; Hannover.

Jerz, H. (1987): Geologische Karte von Bayern 1:25 000, Erläuterungen zum Blatt Nr. 7934 Starnberg Nord. – 128 p., München.

Jerz, H. (1993): Das Eiszeitalter in Bayern – Erdgeschichte, Gesteine, Wasser, Boden. – Geologie von Bayern, 2: 243 p.; Stuttgart (Schweizerbart).

Jerz, H. & Grottenthaler, W. (1995): Quartärprofile mit Paläoböden in Südbayern. – Geologica Bavarica, 99: 179–185; München.

Jerz, H. & Mangelsdorf, J. (1989): Die interglazialen Kalksinterbildungen bei Hurlach nördlich Landsberg am Lech. – Eiszeitalter und Gegenwart, 39: 29–32; Hannover.

Jerz, H. & Schmidt-Kaler, H. (1999): Geologische Karte von Bayern 1:25 000, Erläuterungen zum Blatt Nr. 7234 Ingolstadt. – 86 p., München (Bayerisches Geologisches Landesamt).

Jerz, H., Stephan, W., Streit, R. & Weinig, H. (1975): Zur Geologie des Iller-Mindel-Gebietes. – 37 p., with Geologische Übersichtskarte 1:100 000; München (Bayerisches Geologisches Landesamt).

Jerz, H. & Ulrich, R. (1983): Die Schieferkohlevorkommen von Großweil und Schwaiganger. – Geologica Bavarica, 84: 47–68; München (Bayerisches Geologisches Landesamt).

Jung, W. (1979): Die pflanzlichen Großreste des Riß/Würm-Interglazials von Eurach am Starnberger See/Obb. – Geologica Bavarica, 80: 107–113; München (Bayerisches Geologisches Landesamt).

Jung, W., Beug, H.-J. & Dehm, R. (1972): Das Riß/Würm-Interglazial von Zeifen, Landkreis Laufen a. d. Salzach. – Abhandlungen der Bayerischen Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse, N. F., 151: 131 p.; München.

Keller, O. & Krayss, E. (1998): Datenlage und Modell einer Rhein-Linth-Vorlandvergletscherung zwischen Eem-Interglazial und Hochwürm. – GeoArchaeoRhein, 2: 121–138; Münster.

Keller, O. & Krayss, E. (2005): Der Rhein-Linth-Gletscher im letzten Hochglazial. – Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, 150 (1–2): 19–32; Zürich.

Klasen, N. (2008): Lumineszenzdatierung glazifluvialer Sedimente im nördlichen Alpenvorland. – unpubl. Dissertation Universität zu Köln: 209 p.; Köln.

Kleinmann, A. (1995): Seespiegelschwankungen am Ammersee. Ein Beitrag zur spät- und postglazialen Klimageschichte Bayerns. – Geologica Bavarica, 99: 253–367; München (Bayerisches Geologisches Landesamt).

Kleinschnitz, M. & Kroemer, E. (2003): Geologische Karte von Bayern 1:25 000; Erläuterungen zum Blatt 7233 Neuburg a. d. Donau. – 40 p.; Geologische Karte 1:25 000; München (Bayerisches Geologisches Landesamt).

Kohl, H. (1998): Das Eiszeitalter in Oberösterreich, Teil II – Die eiszeitliche Vergletscherung in Oberösterreich. – Jahrbuch des oberösterreichischen Musealvereins, 143 (1): 175–390; Linz.

Koehne, W. & Niklas, H. (1916): Erläuterungen zur Geologischen Karte des Königreichs Bayern 1:25 000, Blatt Nr. 675 Ampfing. – 96 p.; München.

König, W. (1979): Neuere Forschungsansätze aus dem Gebiet der präwürmzeitlichen Moränen und Schotter des pleistozänen Innvorlandgletschers. – Heidelberger Geographische Arbeiten, 49: 35–46; Heidelberg.

Koenigswald, W. v. (2002): Lebendige Eiszeit – Klima und Tierwelt im Wandel. – 190 p.; Darmstadt (Wissenschaftliche Buchgemeinschaft).

Koenigswald, W. v. & Heinrich, W.-D. (2007): Biostratigraphische Begriffe aus der Säugetierpaläontologie für das Pliozän und Pleistozän Deutschlands. – Eiszeitalter und Gegenwart, 56 (1/2): 96–115; Hannover.

Kovanda, J. (1989): Fossile Mollusken in Kalksinterbildungen (Dauchen) am Lechufer östlich von Hurlach (nördlich Landsberg/Lech). – Eiszeitalter und Gegenwart, 39: 33–41; Hannover.

Kovanda, J. (2006): 'Fagotia-Faunen' und quadriglazialistisches stratigraphisches System des Pleistozäns im nördlichen Alpenvorland im Vergleich zu einigen klassischen Fundorten im Bereich der nordischen Vereisung Deutschlands. – Journal of Geological Sciences, Anthropozoic, 26: 5–37; Prag (Czech Geological Survey).

Kroemer, E. (2010): Fluviale Geomorphodynamik der Donau im Bereich des Rückstaus durch das Isarmündungsgebiet bei Deggendorf (Niederbayern) und Aussagen zur späthochglazialen und spätglazialen Entwicklung. – Bamberger Geographische Schriften 24: 79–87; Bamberg.

Kroemer, E., Veit, A. & Neidinger, S. (2007): Geologische Karte von Bayern, Blatt Nr. 7143 Deggendorf. – Augsburg (Bayerisches Landesamt für Umwelt).

Kromer, B. & Becker, B. (1993): German oak and pine ^{14}C calibration, 7.200 – 9.400 BC. – Radiocarbon, 35: 125–135; Tucson (Arizona).

Leger, M. (1988): Geomorphologie de la vallee subalpine du Danube entre Sigmaringen et Passau. – These de Doctorat, Université de Paris, VII., 3 Bände: 621 p.; Paris.

Lempe, B. (2009): Sind die Verwitterungserscheinungen in Schmelzwasserkiesen geeignet zur Stratigraphie? Vorgestellt am Beispiel von Geologischen Orgeln. – unpubl. Vortrag auf Sitzung der Arbeitsgemeinschaft Alpenvorlandquartär (AGAQ); Kaufering.

Link, A. & Preusser, F. (2005): Hinweise auf eine Vergletscherung des Kemptener Beckens (Südwest-Bayern) im Mittleren Würm. – Eiszeitalter und Gegenwart, 55: 64–87; Hannover.

Litt, Th., Behre, K.-E., Meyer, K.-D., Stephan, H.-J. & Wansa, St. (2007): Stratigraphische Begriffe für das Quartär des norddeutschen Vereisungsgebietes. – Quaternary Science Journal, 56(1–2): 7–65; Hannover.

Litt, Th., Bettis, E. A. III, Bosch, A., Dodonov, A., Gibbard, Ph., Jiaqui, L., Kershaw, P., Koenigswald, W. v., McManus, J., Partridge, T. & Turner, Ch. (in Vorb.): A proposal for the Global Stratotype Section and Point (GSSP) for the Middle/Upper (Late) Pleistocene Subseries boundary. – Unpubl. Manuskript: 36 p.; Bonn.

Litt, Th., Ellwanger, D., Villinger, E. & Wansa, St. (2005): Das Quartär in der Stratigraphischen Tabelle von Deutschland 2002. – Newsletters on Stratigraphy, 41: 385–399; Stuttgart.

Löscher, M. (1976): Die präwürmeiszeitlichen Schotterablagerungen in der nördlichen Iller-Lech-Platte. – Heidelberger Geographische Arbeiten, 45: IX + 157 p.; Heidelberg.

Löscher, M., Münzing, K. & Tillmanns, W. (1978): Zur Paläogeographie der nördlichen Iller-Lech-Platte und zur Genese ihrer Schotter im Altpleistozän. – Eiszeitalter und Gegenwart, 28: 68–82; Öhringen/Württemberg.

Ložek, V. (1964): Quartärmollusken der Tschechoslowakei. – Rozpravy Ústředniho ústravu geologického, 31: 374 p.; Prag.

Maisch, M. (1982): Zur Gletscher- und Klimageschichte des alpinen Spätglazials. – Geographica Helvetica, 37 (2): 93–104; Zürich.

Mayr, F. & Heuberger, H. (1968): Type Areas of Late Glacial and Post-Glacial Deposits in Tyrol, Eastern Alps. – University of Colorado Studies, Series in Earth Sciences: Glaciation of the Alps, 7: 143–165; Boulder.

Megies, H. (2006): Kartierung, Datierung und umweltgeschichtliche Bedeutung der jungquartären Flussterrassen am unteren Inn. – Heidelberger Geographische Arbeiten, 120: 206 p.; Heidelberg.

Miara, St. (1996): Deckschichtenuntersuchungen zur Gliederung der Rißeiszeit beiderseits der Iller im Gebiet des Rhein- und Illergletschers (westliches Alpenvorland, Deutschland). – Jahresberichte und Mitteilungen des oberrheinischen geologischen Vereins, N. F., 78: 359–374; Stuttgart.

Münzing, K. & Ohmert, W. (1974): Mollusken aus dem älteren Pleistozän Schwabens. – Jahrbuch des Geologischen Landesamts Baden-Württemberg, 16: 61–78.

Münzing, K. & Aktas, A. (1987): Weitere Funde molluskenführender Mergellagen im Unteren Deckschotter von Bayerisch-Schwaben. – Jahresberichte und Mitteilungen des oberrheinischen Geologischen Vereins, N. F., 69: 181–193; Stuttgart.

Murphy, M. A. & Salvador, A. (1999): International Stratigraphic Guide – An abridged version. – Episodes, 22: 255–271.

Ohmert, W. (1979): Die Ostracoden der Kernbohrung Eurach 1 (Riß-Eem). – Geologica Bavarica, 80: 127–158; München (Bayerisches Geologisches Landesamt).

Ogg, J. G. & Smith, A. G. (2004): The geomagnetic polarity time scale. – In: Gradstein, F. M., Ogg, J. G. & Smith, A. G. (eds.): Geologic Time Scale 2004: 63–86; Cambridge (University press).

Patzelt, G. (1980): Neue Ergebnisse der Spät- und Postglazialforschung in Tirol. – Jahreshefte der Österreichischen Geographischen Gesellschaft, Zweig Innsbruck, 1976/77: 11–18; Innsbruck.

Patzelt, G. & Bortenschlager, S. (1978): Zur Chronologie des Spät- und Postglazials im Ötztal und Inntal (Ostalpen, Tirol). – In: Frenzel, B. [ed.]: Führer zur Exkursionstagung des IGCP-Projekts 73/1/24: 185–197; Stuttgart-Hohenheim.

Patzelt, G. & Resch, W. (1986): Quartärgeologie des mittleren Tiroler Inntales zwischen Innsbruck und Baumkirchen. – Jahresberichte und Mitteilungen des Oberrheinischen geologischen Vereins, N. F., 68: 43–66; Stuttgart.

Penck, A. (1882): Die Vergletscherung der deutschen Alpen, ihre Ursachen, periodische Wiederkehr und ihr Einfluß auf die Bodengestaltung. – 484 p.; Leipzig (Barth).

Penck, A. (1884): Ueber Periodicität der Thalbildung. – Verhandlungen der Gesellschaft für Erdkunde in Berlin, XI: 39–59; Berlin.

Penck, A. (1899): Die vierte Eiszeit im Bereich der Alpen. Schriften der Vereinigung zur Verbreitung naturwissenschaftlicher Kenntnisse, 39: 1–20.

Penck, A. & Brückner, E. (1901–1909): Die Alpen im Eiszeitalter. – 3 Bände: 1199 p.; Leipzig.

Peschke, P. (1976): Pollenanalytische Untersuchungen an Schieferkohlen aus dem Gebiet von Penzberg und Murnau/Obb. – In: Frenzel, B. [ed.]: Führer zur Exkursionstagung des IGCP-Projektes 73/1/24, 1976: 90–106, Stuttgart-Hohenheim.

Peschke, P. (1983a): Palynologische Untersuchungen interstadialer Schieferkohlen aus dem schwäbisch-oberbayerischen Alpenvorland. – Geologica Bavarica, 84: 69–99; München (Bayerisches Geologisches Landesamt).

Peschke, P. (1983b): Pollenanalysen der Schieferkohlen von Herrnhausen (Wolfratshausener Becken/Obb.) – ein Beitrag zum Problem interglazialer Ablagerungen in Oberbayern. – Geologica Bavarica, 84: 107–121; München (Bayerisches Geologisches Landesamt).

Piller, W. E., Egger, H., Erhart, C. W., Gross, M., Harzhauser, M., Hubmann, B., van Husen, D., Krenmayr, H.-G., Krystyn, L., Lein, R., Lukeneder, A., Mandl, G. W., Rögl, F., Rötzel, R., Rupp, Ch., Schnabel, W., Schönlaub, H. P., Summesberger, H., Wagreich, M. & Wessely, G. (2004): Die stratigraphische Tabelle von Österreich 2004 (sedimentäre Schichtfolgen). – 1. Aufl.; Wolkersdorf (Österreichische Stratigraphische Kommission).

Preusser, F. (2004): Towards a chronology of the Late Pleistocene in the northern Alpine Foreland. – Boreas, 33: 195–210; Oslo.

Preusser, F. (2010): Stratigraphische Gliederung des Eiszeitalters in der Schweiz (Exkursion D am 8. April 2010). – Jahresberichte und Mitteilungen des oberrheinischen geologischen Vereins, N. F., 92: 83–98; Stuttgart.

Preusser, F., Hajdas, I., Ivy-Ochs, S. [ed.] (2008): Recent progress in Quaternary dating methods. – Quaternary Science Journal (Eiszeitalter und Gegenwart), 57 (1/2): 252 p.; Stuttgart.

Reitner, J. (2007): Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications. – Quaternary International, 164/165: 64–84.

Rähle, W. (1994): Molluskenfaunen der Kiesgruben Münster S Rain am Lech und Lauter, Bobingen. – unpubl. Bericht; Tübingen.

Rähle, W. (1995): Altpleistozäne Molluskenfaunen aus dem Zusamplattenschottern und ihrer Flußmergeldecke vom Uhlenberg und Lauterbrunn (Iller-Lech-Platte, Bayerisch Schwaben). – Geologica Bavarica, 99: 103–118; München (Bayerisches Geologisches Landesamt).

Reich, H. (1953): Die Vegetationsentwicklung der Interglaziale von Großweil-Ohlstadt und Pfefferbichl im Bayerischen Alpenvorland. – Flora, 140: 386–443; Jena.

Reuther, A. U. (2007): Suface exposure dating of glacial deposits from the last glacial cycle – Evidence from the Eastern Alps, the Bavarian Forest, the Southern Carpathians and the Altai Mountains. – Relief, Boden, Paläoklima: 196 p.; Stuttgart (Schweizerbart).

Rögner, K. (1979): Die glaziale und fluvioglaziale Dynamik im östlichen Lechgletschervorland – ein Beitrag zur präwürmzeitlichen Pleistozän-Stratigraphie. – Heidelberger Geographische Arbeiten, 49: 67–138; Heidelberg.

Rögner, K. (1993): Ein fossiler Boden östlich von Mindelheim und seine stratigraphische Bedeutung. – Mitteilungen der Geographischen Gesellschaft München, 78: 5–18; München.

Rögner, K. (2002): Zum Quartär auf Blatt Markt Rettenbach. – Münchner Geographische Abhandlungen, A52: 17–43; München.

Rögner, K. (2004): Ein Vorschlag zur Gliederung pleistozäner Ablagerungen im deutschen Alpenvorland basierend auf Ergebnissen aus der südlichen Iller-Lech-Platte. – Mitteilungen der Geographischen Gesellschaft in München, 87: 235–273; München.

Rögner, K. & Löscher, M. (1987): Quartäre Sedimentations- und Verwitterungsphasen bei Hinterschmalholz (Regierungsbezirk Schwaben). – Mitteilungen der Geographischen Gesellschaft München, 72: 161–170; München.

Rögner, K. & Löscher, M. (1993): Die fluvial-periglazialen Schotter östlich Memmingen (Bayerisch Schwaben). – Mitteilungen der Geographischen Gesellschaft in München, 78: 85–111; München.

Rögner, K., Löscher, M. & Zöller, L. (1988): Stratigraphie, Paläogeographie und erste Thermolumineszenzdatierungen in der westlichen Iller-Lech-Platte (Nördliches Alpenvorland). – Zeitschrift für Geomorphologie, N. F., Supplement-Band, 70: 51–73; Stuttgart.

Roppelt, Th. (1988): Die Geologie der Umgebung von Obergünzburg im Allgäu mit sedimentpetrographischen Untersuchungen der glazialen Ablagerungen. – unpublizierte Disseration Technische Universität München: 109 S., Geologische Karte 1:25 000; München.

Salvador, A. (1994): International Stratigraphic Guide. – Geological Society of America: 214 p.; Boulder.

Schaefer, I. (1953): Die donaueiszeitlichen Ablagerungen an Lech und Wertach. – Geologica Bavarica, 19: 13–64; München (Bayerisches Geologisches Landesamt).

Schaefer, I. (1955): Sur la division du Quaternaire dans l'avant pays des Alpes en Allemagne. – Actes IV. Congress International du Quaternaire (INQUA), Rome/Pise, 1953, vol. 2: 910–914.

Schaefer, I. (1957): Erläuterungen zur Geologischen Karte von Augsburg und Umgebung 1:50 000, mit einem paläontologischen Beitrag von R. Dehm. – 92 p.; München (Bayerisches Geologisches Landesamt).

Schaefer, I. (1975): Die Altmoränen des diluvialen Isar-Loisachgletschers und ihr Verständnis aus der Kenntnis der Paareiszeit. – Mitteilungen der Geographischen Gesellschaft München, 60: 115–153; München.

Schaefer, I. (1980): Der angebliche 'altpleistozäne Donaulauf' im schwäbischen Alpenvorland. – Jahresberichte und Mitteilungen des oberrheinischen geologischen Vereins, N. F., 62: 167–198; Stuttgart.

Schedler, J. (1979): Neue pollenanalytische Untersuchungen am Schieferkohlevorkommen des Uhlenberges bei Dinkelscherben (Schwaben). – Geologica Bavarica, 80: 165–182; München (Bayerisches Geologisches Landesamt).

Schellmann, G. (1990): Fluviale Geomorphodynamik im jüngeren Quartär des unteren Isar- und angrenzenden Donautales. – Düsseldorfer Geographische Schriften, 29: 131 p.; Düsseldorf (Geographisches Institut der Universität).

Schellmann, G. (2010): Neue Befunde zur Verbreitung, geologischen Lagerung und Altersstellung der würmzeitlichen (NT 1 bis NT3) und holozänen (H1 bis H7) Terrassen im Donautal zwischen Regensburg und Bogen. – Bamberger Geographische Schriften 24: 1–77.

Schellmann, G., Irmler R. & Sauer, D. (2010): Zur Verbreitung, geologischen Lagerung und Altersstellung der Donauterrassen auf Blatt L7141 Straubing. – Bamberger Geographische Schriften 24: 79–168.

Scheuenpflug, L. (1971): Ein alteiszeitlicher Donaulauf in der Zusamplatte (Bayerisch Schwaben). – Berichte der Naturforschenden Gesellschaft Augsburg, 27: 3–10; Augsburg.

Scheuenpflug, L. (1979): Der Uhlenberg in der östlichen Iller-Lech-Platte (Bayerisch Schwaben). – Geologica Bavarica, 80: 159–164; München (Bayerisches Geologisches Landesamt).

Schirmer (1983): Die Talentwicklung an Main und Regnitz seit dem Hochwürm. – Geologisches Jahrbuch, A 71: 11–43; Hannover.

Schlüchter, Ch. & Kelly, M. A. (2000): Das Eiszeitalter in der Schweiz. – Überarbeiteter Neudruck, Stiftung Landschaft und Kies; Uttingen.

Schlüchter, Ch. (1989): Thalgut: Ein umfassendes eiszeitstratigraphisches Referenzprofil im nördlichen Alpenvorland. – Eclogae geologicae Helvetiae, 82: 277–284; Basel.

Schmidt, M. (1911): Rückzugsstadien der Würmvergletscherung im Argengebiet. – Schriften des Vereins für die Geschichte des Bodensees; 40: 1–27.

Schneider, M. (1995): Der hochwürmzeitliche Rückzug des Eisrandes im Ammersee-Lobus des Loisach-Gletschers – Zur Frage eines ehemals erhöhten Seespiegels. – Geologica Bavarica, 99: 223–244, München (Bayerisches Geologisches Landesamt).

Schneider, Th. (2006): Schwemmkegel-, Talsohlen und Moorentwicklung am Alpennordrand im Spät- und Postglazial. – Geographica Augustana, 1: 338 p.; Augsburg.

Schreiber, U. (1985): Das Lechtal zwischen Schongau und Rain im Hoch-, Spät- und Postglazial. – Geologisches Institut der Universität zu Köln, Sonderveröffentlichungen, 58: 192 p.; Köln.

Schreiner, A. (1989): Zur Stratigraphie der Rißeiszeit im östlichen Rheingletschergebiet (Baden-Württemberg). – Jahreshefte des Geologischen Landesamtes Baden-Württemberg, 31, 183–196.

Schreiner, A. (1996): Die Einführung der Haslacheiszeit und die 3-Teilung der Risseiszeit im östlichen Rheingletschergebiet (SW-Deutschland). – Eclogae geologicae Helvetiae, 89 (3): 991–1005; Basel.

Schreiner, A. (1997): Einführung in die Quartärgeologie. – 2. Aufl.: 257 p.; Stuttgart (Schweizerbart).

Schreiner, A. & Ebel, R. (1981): Quartärgeologische Untersuchungen in der Umgebung von Interglazial-Vorkommen im östlichen Rheingletschergebiet (Baden-Württemberg). – Geologisches Jahrbuch, A59: 3–64.

Schröder, J. & Dehm, R. (1951): Die Molluskenfauna aus der Lehm-Zwischenlage des Deckenschotters von Fischach, Kreis Augsburg. – Geologica Bavarica, 6: 118–120; München (Bayerisches Geologisches Landesamt).

Semmel, A. (1968): Studien über den Verlauf jungpleistozäner Formung in Hessen. – Frankfurter Geographische Hefte, 45: 133 p.; Frankfurt a. M.

Sinn, P. (1972): Zur Stratigraphie und Paläogeographie des Präwürm im mittleren und südlichen Illergletscher-Vorland. – Heidelberger Geographische Arbeiten, 37: 159 pp.

Starnberger, R., Terhorst, B., Rähle, W., Peticka, R. & Haas, J. N. (2008): Palaeoecology of Quaternary periglacial environments during OIS-2 in the forefields of the Salzach Glacier (Upper Austria). – Quaternary International, 198: 51–61.

Steininger, F. F. & Piller, W. E. (1999): Empfehlungen (Richtlinien) zur Handhabung der stratigraphischen Nomenklatur. – Courier des Forschungsinstituts Senckenberg, 209: 1–19; Frankfurt.

Strattner, M. & Rolf, Ch. (1995): Magnetostratigraphische Untersuchungen an pleistozänen Deckschicht-Profilen im bayerischen Alpenvorland. – Geologica Bavarica, 99: 55–101; München (Bayerisches Geologisches Landesamt).

Tillmanns, W. (1977): Zur Geschichte von Urmain und Urdonau zwischen Bamberg, Neuburg/Donau und Regensburg. – Sonderveröffentlichungen des Geologischen Instituts der Universität zu Köln, 30: 198 p.; Köln.

Tillmanns, W., Brunnacker, K. & Löscher, M. (1983): Erläuterungen zur Geologischen Übersichtskarte der Aindlinger Terrassentreppe zwischen Lech und Donau 1:50 000. – Geologica Bavarica, 85: 31 p.; München (Bayerisches Geologisches Landesamt).

Tillmanns, W., Münzing, K., Brunnacker, K. & Löscher, M. (1982): Die Rainer Hochterrasse zwischen Lech und Donau. – Jahresberichte und Mitteilungen des oberrheinischen geologischen Vereins, N. F., 64: 79–99, Stuttgart.

Traub, F. & Jerz, H. (1976): Ein Lößprofil von Duttendorf (Oberösterreich) gegenüber Burghausen an der Salzach. – Zeitschrift für Gletscherkunde und Glazialgeologie, 11: 175–193; Innsbruck.

Troll, C. (1924): Der diluviale Inn-Chiemseegletscher – Das geographische Bild eines typischen Alpenvorlandgletschers. – Forschungen zur deutschen Landes- und Volkskunde, 23: 1–121.

van Husen, D. (2000): Geological Processes during the Quaternary. – Mitteilungen der Österreichischen Geologischen Gesellschaft, 92: 135–156; Wien.

Villinger, E. (2003): Zur Paläogeographie von Alpenrhein und oberer Donau. – Zeitschrift der deutschen Geologischen Gesellschaft, 154 (2-3): 193–253, Stuttgart..

Walker, M., Johnsen, S., Rasmussen, S. O., Popp, T., Steffensen, J.-P., Gibbard, Ph., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L. C., Hughen, K., Kershaw, P., Kromer, B., Litt, Th., Lowe, D. J., Nakagawa, T., Newnham, R. & Schwander, J. (2008): Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP icecore and selected auxiliary records. – Journal of Quaternary Science, 24 (1): 3–17; (Wiley).

Walker, M., Johnsen, S., Rasmussen, S. O., Steffensen, J.-P., Popp, T., Gibbard, Ph., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L., Hughen, K., Kershaw, P., Kromer, B., Litt, Th., Lowe, D. J., Nakagawa, T., Newnham, R. & Schwander, J. (2008): The Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch (Quaternary System/Period) in the NGRIP ice core. – Episodes, 31 (2): 264–267; Beijing.

Wansa, St., Hoselmann, Ch., Katzschmann, L. & Stephan, H.-J. (2008): Das Quartär im Lithostratigraphischen Lexikon von Deutschland. – Abhandlungen der Geologischen Bundesanstalt,Tagungsband DEUQUA 2008: 235–237; Wien.

Zagwijn, W. H. (1989): The Netherlands during the Tertiary and the Quaternary; A Case History of Coastal Lowland Evolution. – Geologie en Mijnbow, 68: 116; Dordrecht.

Zagwijn, W. H. & De Jong, J. (1985): Die Interglaziale von Bavel und Leerdam und ihre stratigraphische Stellung im Niederländischen Früh-Pleistozän. – Mededelingen van de Rijks Geologische Dienst, 37(3): 155–169.

Zollinger, G. (1991): Zur Landschaftsgenese und Quartärstratigraphie am südlichen Oberrheingraben – am Beispiel der Lössdeckschichten der Ziegelei Allschwil (Kanton Basel-Landschaft). – Eclogae geologicae Helvetiae, 84 (3): 739–752; Basel.

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An Outline of the Quaternary Stratigraphy of Austria

Dirk van Husen, Jürgen M. Reitner

Abstract: An overview of the Quaternary Stratigraphy in Austria is given. The subdivision of the mappable depositional units is based partly on criteria of lithostratigraphy (lithic properties) and allostratigraphy (e.g. unconformities). Traces of glaciations are missing for the Early Pleistocene period (2.58–0.78 Ma). The few and isolated sediment bodies are documenting fluvial accumulation and loess deposition along the rivers. Paleomagnetically correlated loess-paleosol-sequences like the profil at Stranzendorf including the Gauss/Matuyama boundary respectively Neogen/Quaternary are documenting slightly warmer condition than during during the Middle Pleistocene (0.78–0.13 Ma) which is in accordance with the global $\delta^{18}O$ record.
Four major glaciations (Günz, Mindel, Riß, Würm) are proved during Middle and Late Pleistocene. All of these are documented by proglacial sediments topped by basal till, terminal moraines linked with terrace bodies and loess accumulation as well. This allows to recognize the climatic steering of sedimentation in context with advancing glaciers and the dispersion of permafrost and congelifraction as far as into the Alpine foreland.
Both youngest major glaciations (Riß and Würm) are correlated according to geochronological data with the Marine Isotope Stages (MIS) 6 and 2. The simultaneousness of Günz and Mindel with the phases of massive global climatic deterioration during MIS 16 and 12 seems plausible. Phases of less climatic deterioration and consequently glaciations have been found only in loess profiles like Krems Schießstätte so far.

[Ein Abriss der Quartär-Stratigraphie von Österreich]

Kurzfassung: Es wird ein Überblick über die in Österreich verwendete Quartär-Stratigraphie gegeben. Die stratigraphische Gliederung der kartierbaren Sedimenteinheiten basiert teilweise auf Kriterien der Lithostratigraphie (lithologischer Eigenschaften) und jenen der Allostratigraphie (z.B. Diskonitinuitäten).
Für das Altpleistozän (2.58–0.78 Ma) fehlen bis jetzt Spuren einer Vergletscherung. Die wenigen und isolierten Sedimentvorkommen belegen fluviatile Akkumulation und Lössablagerung in der Umgebung der Flüsse. Paläomagnetisch korrelierte Löss-Paläoboden – Sequenzen wie das Profil Stranzendorf mit der Gauss/Matuyama – Grenze bzw. Neogen/Quartär – Grenze dokumentieren in Übereinstimmung mit den globalen $\delta^{18}O$ Werten etwas wärmere Bedingungen als im Mittelpleistozän (0.78–0.13 Ma).
Vier Großvergletscherungen (Günz, Mindel, Riß und Würm) sind für Mittelpleistozän und Jungpleistozän belegt. Diese sind mit Sedimenten aus der Vorstoßphase überlagert von Grundmoräne, Endmoränen im Alpenvorland und damit verknüpfte Terrassenschüttungen sowie Lössakkumulation dokumentiert. Daraus ist die klimagesteuerte Sedimentation im Zusammenhang mit dem Vorstoß der Gletscher, der Ausbreitung des Permafrostes und der Frostschuttbildung bis ins Vorland erkennbar.
Die jüngsten Großvergletscherungen Riß und Würm werden aufgrund geochronologischer Daten mit den Marinen Isotopenstufen (MIS) 6 und 2 korreliert. Für Günz und Mindel scheint eine Gleichzeitigkeit mit den Phasen massiver globaler Klimaverschlechterung während MIS 16 und MIS 12 plausibel. Dokumente für die schwächeren Glaziale wurden bisher nur in Lössprofilen (z.B. Krems Schießstätte) gefunden.

Keywords: *Alps, stratigraphy, Quaternary, Early Pleistocene, Middle Pleistocene, Late Pleistocene, glaciation, glacial deposits, landscape evolution*

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The stratigraphic subdivision of the sedimentary archive of Austria attributed to the Quaternary (the last 2.58 Ma, Gibbard et al. 2009) represents a big challenge for two reasons at least. First, very different former environments (ranging from glacial, fluvio-glacial, to lacustrine and eolian) and facies associations whose sedimentary record is fragmentary and discontinuous, are documented in the Austrian landscape for the Pleistocene (2.58 Ma–0.01 Ma BP). Such a complex setting leads to the second reason for problems in establishing a homogeneous stratigraphic approach. Only few sedimentary units in inneralpine, mostly glacially shaped basins can be classified according to the principles of lithostratigraphy (North American Commission on Stratigraphic Nomenclature [NACSN] 2005) i.e. using lithic characteristics and the Law of Superposition. However, it is evident that fluvio-glacial or fluvial deposits in the Alpine Foreland, having more or less the same lithic content during all Quaternary phases of sedimentation but occurring in different but contiguous terrace levels and documenting different phases of aggradation followed by incision, represent discontinuity-bound units in the sense of allo-stratigraphy (NACSN 2005). As these units cannot be treated according to the lithostratigraphic criteria mentioned above, any stratigraphic subdivision within this setting has to rely on a mixture of different criteria for discriminating sedimentary units mappable at least at the scale of 1:10,000.

The stratigraphy and stratigraphic terminology currently in use is the result of a scientific development beginning in the middle of the 19th century when glacial deposits in the Alps as well as intercalated sediments bearing organic material like the Hötting breccia (see Penck 1921) gained attention. The Eastern Alps and their foreland (including parts of Upper Austria) resemble the type-area for the classical Alpine stratigraphy according to Penck & Brückner

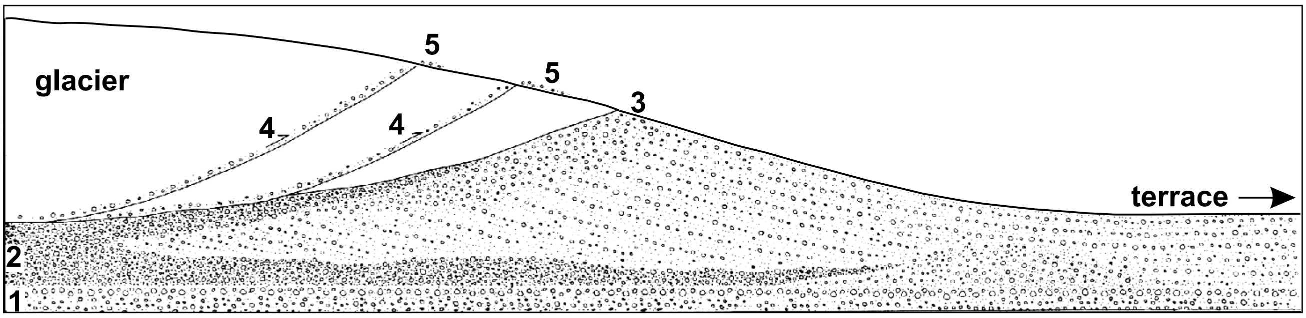

Fig. 1: Schematic sketch showing the principal sedimentary units at the glacier terminus and the transition to a proglacial terrace. 1: proglacial gravel of the glacier advance phase ("Vorstoßschotter", "Vorstoßsedimente") 2: (overconsolidated) basal till 3: terminal moraine 4: thrust with basal debris 5: supraglacial debris transported predominantly by debris flows

Abb. 1: Schematische Skizze mit der Darstellung der prinzipiellen Sedimentkörper am Gletscherende und am Übergang zur Terrasse im Gletschervorfeld. 1: „Vorstoßschotter", „Vorstoßsedimente" 2: (überkonsolidierte) Grundmoräne 3: Endmoräne 4: Scherfläche mit basalem Schutt 5: supraglazialer Schutt überwiegend in Form von Schlammströmen bis Muren transportiert.

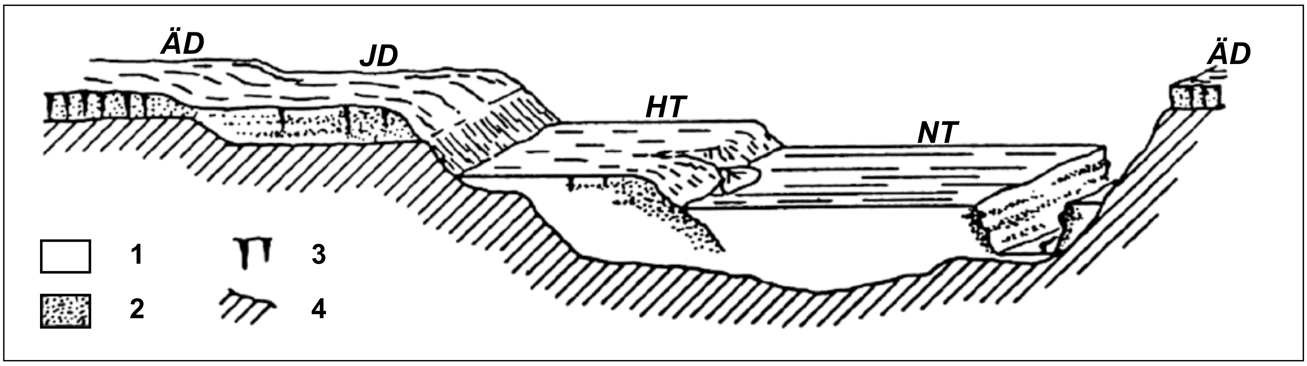

Fig. 2: Schematic sketch of the typical sequence of terraces in the foreland of the Eastern Alps (from van Husen, 1986). 1: unweathered gravel 2: conglomeratic parts 3: Geologische Orgel (pipe-like weathering structure), 4: Pre-Quaternary bedrock. NT: Niederterrasse (Würm), HT: Hochterrasse (Riß); JD Jüngere Deckenschotter (Mindel); ÄD: Ältere Deckenschotter (Günz).

Abb. 2: Schematische Skizze mit der typischen Terrassensequenz im Vorland der Ostalpen. 1: unverwitterte Kiese 2: konglomerierte Bereiche 3: geologische Orgeln 2: präquartärer Untergrund. NT: Niederterrasse (Würm) HT: Hochterrasse (Riß) JD: Jüngere Deckenschotter (Mindel) ÄD: Ältere Deckenschotter (Günz).

(1909) with the *Günz*, *Mindel*, *Riß* and *Würm* glaciations based on the concept of "Glaziale Serie" genetically linking tongue basins with basal till, terminal moraine deposits and terraces consisting of proglacial outwash (compare Fig. 1). Terrace bodies and moraines of the four glaciations differ in the degree of weathering (Fig. 2) and the characteristics of cover beds (e.g. loess/paleosol assemblages). Cases of superposition are rare (e.g. near Munich/Bavaria). In the Austrian part of the Alpine foreland which was affected by tectonic uplift, outwash terraces were correlated based on the criteria mentioned above in the context of their morphological position within the valley, with the oldest ones in the highest position.

This stratigraphic scheme which is reduced by some authors (e.g. Bowen 1978) to include solely the element of morphological correlation, classifying it as morphostratigraphy, has been extended and adapted in the sense of climate-based stratigraphy. However the deposits of most glacials and also some interglacials, stadials and interstadials do not cover geological time without gaps, which would be required for a (regional) chronostratigraphy (Gibbard & West 2000). Thus no regional chronostratigraphic subdivision sensu stricto exists for the Quaternary sediments of Austria, with the exception of the Würm glacial period which was officially classified as a stage by the Subcommission on European Stratigraphy (SEQS; Chaline & Jerz, 1984). It is subdivided into three substages: Lower (Early), Middle and Upper (Late) Würm based on palynological and lithological criteria evident in strato-types. The other glacials and at least the last interglacial (Riss/Würm-Interglacial), which represents the Alpine equivalent of the Eemian (Grüger 1979) are informally used in the sense of stages. The Marine Isotope Stages (MIS; see Gibbard & Cohen 2008, Cohen & Gibbard 2011) provide the chronostratigraphic framework (Fig. 3) within which the climate-based units (e.g. Günz glacial) are correlated (van Husen 2000a) based on the existing geochronological and biostratigraphic constraints, whose quality and precision decreases in most cases with the age of the deposit. In the case of the Middle Pleistocene glaciations Günz and Mindel which fall into the Brunhes epoch (van Husen 2000a) it is inferred that they are concurrent with phases of global excess 100-kyr ice as a result of unusually long intervals of low summer insolation, which are followed by major Terminations as evident in the $\delta^{18}O$ record (Raymo 1997). Such a situation is true based on geochronological data at least for the other major glaciations during Riss (MIS 6) and (Upper / Late) Würm (MIS 2). With the knowledge on the course of these two major climatic deteriorations and their impact on the Alpine sedimentary record, a correlation of the older glaciations with the marine $\delta^{18}O$ stratigraphy seems possible based on the relation between type and magnitude of the global climate signal and the amount of reconstructed sediment production (van Husen & Reitner 2011).

Short Outline of the Stratigraphy as Linked to Landscape Development

The description of the system of Quaternary sedimentary units of the Middle to Late Pleistocene is based on the succession of cold (glacial) and warm (interglacial) periods shown by the $\delta\ ^{18}O$ record (Raymo 1997, van Husen 2000a; see Fig. 3). All these varying global climatic conditions had an impact on processes shaping the landscape of the Alps in relation to the respective magnitude of the climate signal. Thus expansion of permafrost, strong congelifraction and the vegetation cover changed simultaneously with growing and shrinking of the valley glaciers. These changes occurred in higher or lower parts of the Alps or in the foreland depending on the degree of climatic deterioration (van Husen 2000a). Beside the great events (glaciations) resulting in glacier expansion into the foreland, climatic deteriorations are often documented in loess profiles only (e.g. Krems Schießstätte). The corresponding gravel beds, if ever formed and preserved, have not been recognized so far. Periglacial debris production and gravel accumulation prograded successively from the inneralpine areas to the foreland during climatic deterioration, finally forming extended terraces along the rivers (Danube and tributaries) probably only during the four climax periods. The parallelization of separated bodies of terminal moraines of the former network of valley glaciers and transient glaciers was done in consideration of the laws of ice dynamic. Isolated terraces have been correlated according to their surface gradient as well as to their base level in relation to the recent river (Fig. 2). In both cases this is supported by lithology, sedimentary facies, morphology, development of weathering and loess cover (Piller, van Husen & Schnabel 2003).

According to these principal climatically controlled sedimentary and erosional processes it is possible to trace the four terraces (Penck & Brückner 1909) along the Danube and the tributaries down-stream to the Vienna Basin (Figs. 4, 5, 6 & 7) due to a uniform and quite stable tectonic situation. Within the Vienna basin such a tectonic setting seems to be present only in the westernmost part (the city of Vienna). East of the Leopoldsdorfer fault and at the centre of the Vienna Basin recent tectonic subsidence is taking place (Decker, Peresson & Hinsch 2005) influencing the deposits of the two youngest glaciations (Gänserndorfer and Prater Terrasse) north of the river Danube and forming the Mitterndorfer Senke (Mitterndof Basin) south of it. Between these two areas of active subsidence a zone of less tectonic influence runs parallel to the river (Rauchenwarter Platte – Maria Ellender Hügelland – Prellenkirchner Terrasse) where the gravel accumulations of Lower and Middle Pleistocene seem to be in accordance with the terraces west of the Vienna basin (Fuchs 1985a, 1985b, 1985c). Therefore local names (e.g. Fuchs 1964, 1985a, 1985b, 1985c) are not added to the table in Fig. 3 but mentioned here as synonyms.

For the period of the Early Pleistocene no traces of glaciations have been found. However, the succession of cool and warm periods during this time had an effect on landscape evolution especially in the Alpine forelands in the North and Southeast. Thus gravel accumulation along the rivers combined with loess deposition in the surrounding area took place more or less in the same way but under slightly warmer conditions than during the Middle Pleistocene (van Husen 2000a). Some remnants of these sediments belonging to this long period before the major glaciations began, are included in the table (Fig. 3).

Lateglacial deposits like glacial sediments of prominent stadials are not within the scope of this review. Overviews on the stratigraphic terminology of this timespan have been given by van Husen (1997), Reitner (2007), and Ivy-Ochs et al. (2009).

This review aims to present the currently used Quaternary stratigraphic subdivision based on mappable bodies of sediments. In addition, three major long sections (Stranzendorf, Krems Schießstätte and Mitterndorf Basin) and an important area with fossil rich cave sediments are presented which are crucial for the understanding of Quaternary landscape evolution and have the potential to serve as reference sections for future local chronostratigraphic subdivisions.

The chronostratigraphic framework for the Quaternary is given by the major chronostratigraphic subdivisions according to the standards presented by Gibbard et al. (2009) with the Early/Middle Pleistocene boundary at the Matuyama-Brunhes paleomagnetic Chron boundary following the recommendation by Richmond (1996) and Head & Gibbard (2005) and the Middle/Late Pleistocene boundary at the beginning of the Eemian (Gibbard 2003) roughly identical with the base of the MIS 6/5 boundary. In addition the record of the Marine Isotope stages serves as a global chronostratigraphic reference.

The localities of stratigraphic units are displayed in the Figures 4, 5, 6, or 7. It is important to note that the Austrian landscape is subdivided into four elements: the Alps, the Northern Alpine Foreland (representing the predominant part of the Molasse Basin) drained by the river Danube and its southern tributary rivers (Inn, Traun, Enns, Ybbs and Traisen), the Vienna Basin and the Styrian Basin located in the southeast drained by the river Mur and its tributaries. The stratigraphic subdivisions with their interrelationships and the correlations – partly well established, partly inferred – with the chronostratigraphic frame are summarized in the table in Fig. 3.

Early Pleistocene Units

Geiersberg Schotter

This unit is described by Graul (1937) and Rupp (2008). The type locality is situated east of the city of Ried im Innkreis (location see Fig. 5) on ÖK 1:50,000 sheet 47 Ried im Innkreis. The name originates from the small village Geiersberg. The Geiersberg Schotter (in English: Geiersberg gravel) are small remnants of a former gravel accumulation north of the Kobernaußer Wald (Rupp 2008). They unconformably overlay the Neogene deposits of the Molasse Basin.

The gravel deposit is dominated by quartz and quartzite with some crystalline and a few limestone pebbles. The heavily oxidized and weathered gravel shows coarse bedding with thick sand layers and consists of eroded and redeposited material of the Neogene Hausruck Formation.

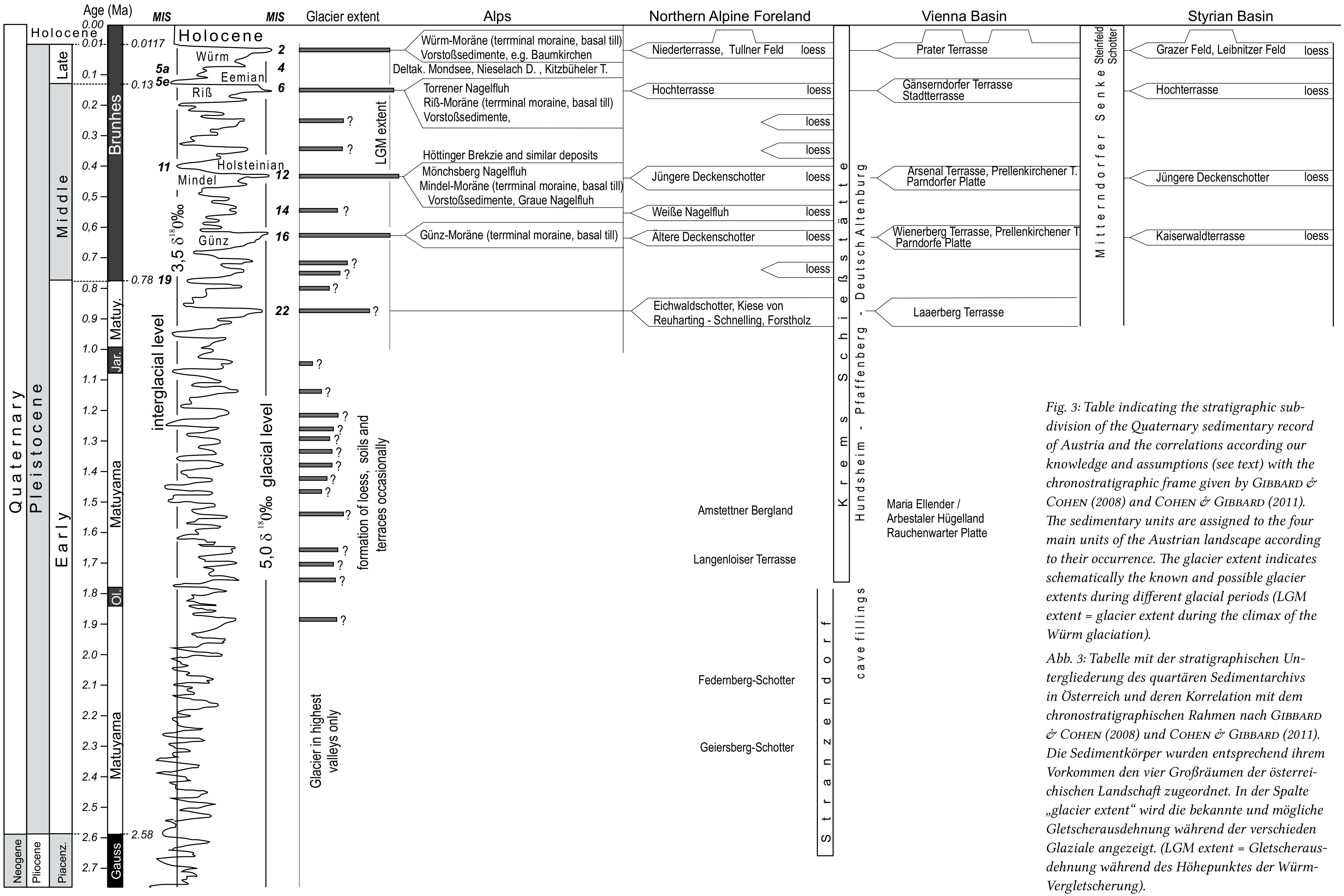

Fig. 3: Table indicating the stratigraphic subdivision of the Quaternary sedimentary record of Austria and the correlations according our knowledge and assumptions (see text) with the chronostratigraphic frame given by GIBBARD & COHEN *(2008) and* COHEN & GIBBARD *(2011). The sedimentary units are assigned to the four main units of the Austrian landscape according to their occurrence. The glacier extent indicates schematically the known and possible glacier extents during different glacial periods (LGM extent = glacier extent during the climax of the Würm glaciation).*

Abb. 3: Tabelle mit der stratigraphischen Untergliederung des quartären Sedimentarchivs in Österreich und deren Korrelation mit dem chronostratigraphischen Rahmen nach GIBBARD & COHEN *(2008) und* COHEN & GIBBARD *(2011). Die Sedimentkörper wurden entsprechend ihrem Vorkommen den vier Großräumen der österreichischen Landschaft zugeordnet. In der Spalte „glacier extent" wird die bekannte und mögliche Gletscherausdehnung während der verschieden Glaziale angezeigt. (LGM extent = Gletscherausdehnung während des Höhepunktes der Würm-Vergletscherung).*

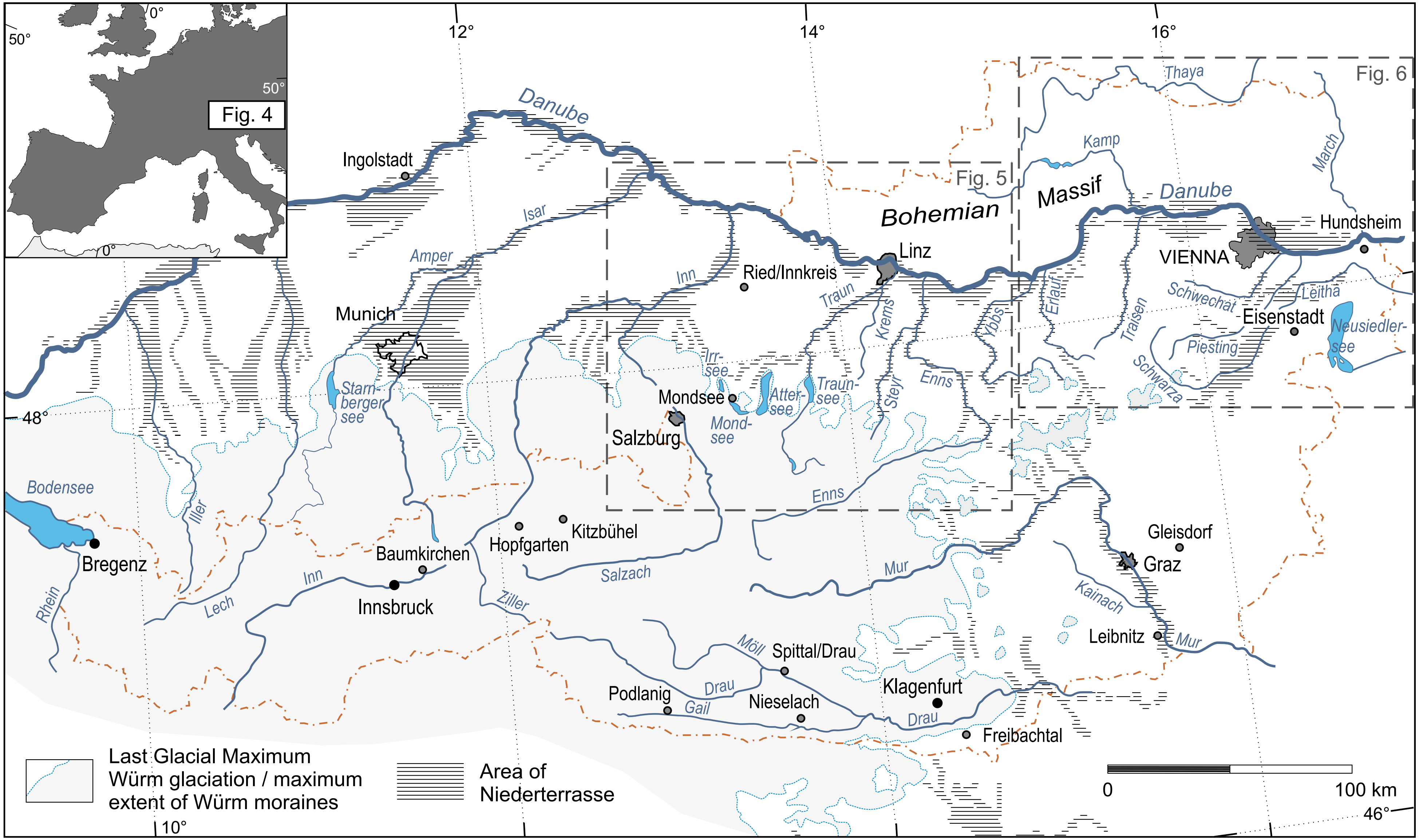

Fig. 4: Key map of the Quaternary landscape of Austria with the limit of the last glaciation (Würm) and its outwash deposits (Niederterrasse) (after VAN HUSEN 2000a). All localities mentioned in the text are shown in this figure or in detailed maps of Figs. 5, 6 & 7.

Abb. 4: Karte der quartären Landschaft von Österreich mit der Ausdehnung der letzten Vergletscherung (Würm) und deren Schmelzwasserablagerungen (Niederterrasse) (nach VAN HUSEN 2000a). Alle im Text erwähnten Lokalitäten sind in dieser Abbildung oder den Detailkarten (Abb. 5, 6 und 7) zu finden.

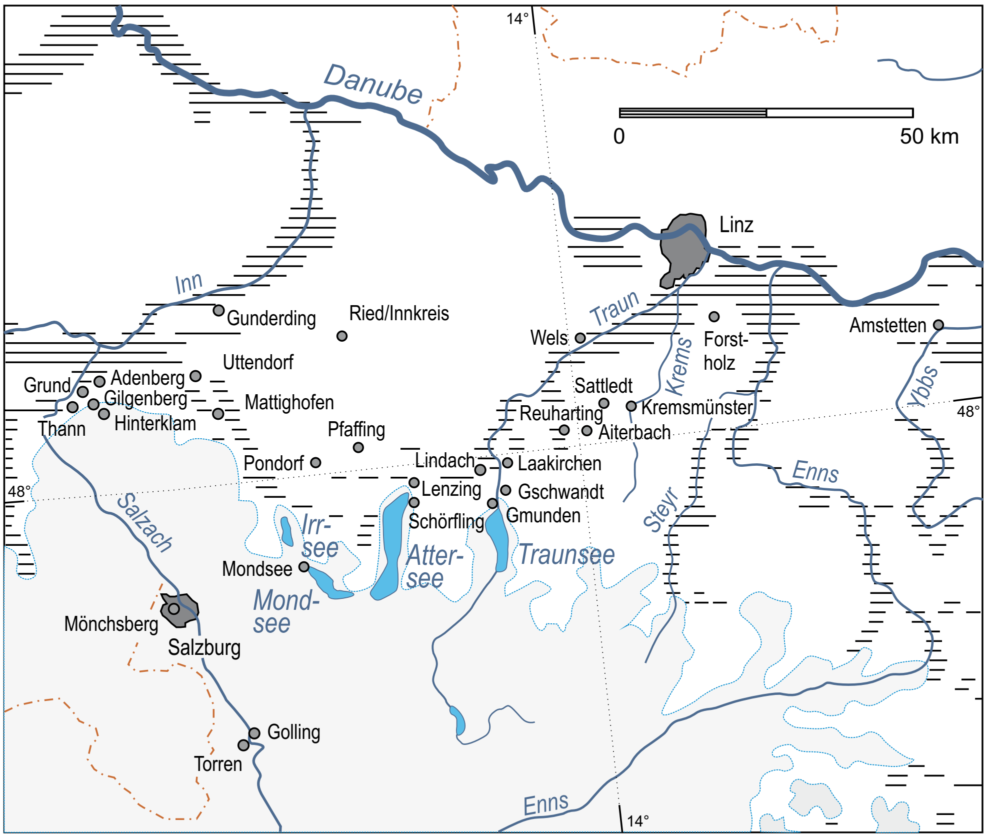

Fig. 5: Detailed map showing all localities between Salzburg and Linz. For legend see Fig. 4.

Abb. 5: Detailkarte aller Lokalitäten zwischen Salzburg und Linz. Für die Legende siehe Abb. 4.

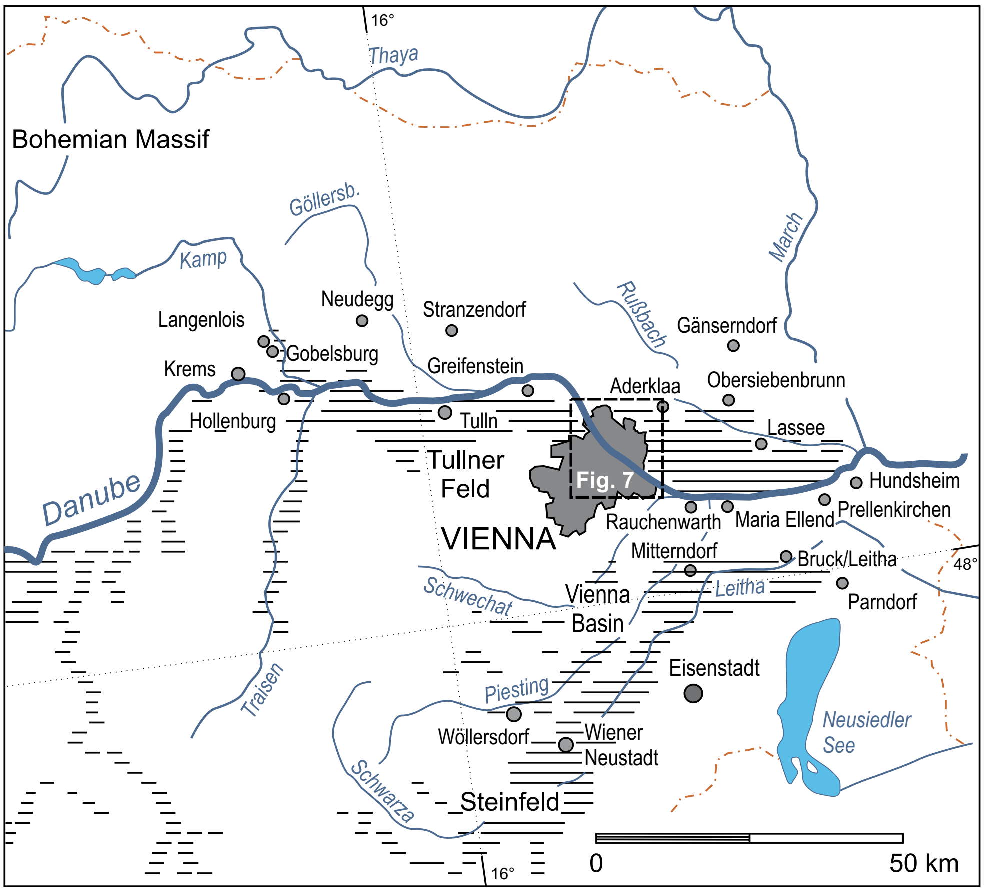

Fig. 6: Detailed map indicating all relevant localities in the NE of Austria close to Vienna. For legend see Fig. 1. The black frame of Fig. 7 is indicated.

Abb. 6: Detailkarte aller relevanten Lokalitäten im Nordosten von Österreich in der Umgebung von Wien. Für die Legende siehe Abb. 4. Der schwarze Rahmen zeigt die Ausdehnung der Detailkarte in Abb. 7.

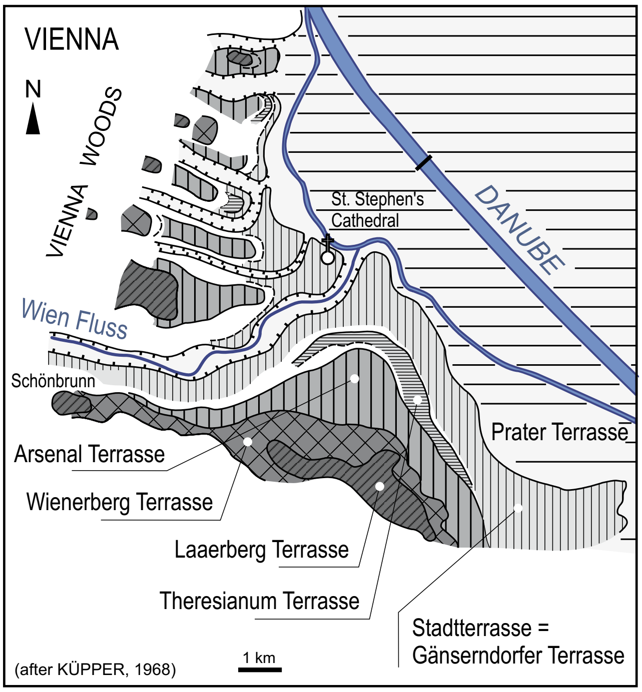

Fig. 7: Detailed map showing the classical terrace system in Vienna.

Abb. 7: Detailkarte mit dem klassischen Terrassensystem im Stadtgebiet von Wien.

The chronostratigraphic age is assumed to correlate with a cold period during Early Pleistocene which is much older than the period when the Federnberg Schotter were formed.

Federnberg Schotter

The description of this unit meaning Federnberg gravel in English is given by Graul (1937) and Rupp (2008). The type area is situated west of the city of Ried im Innkreis (location see Fig. 5) on ÖK 1:50,000 sheet 47 Ried im Innkreis. The name originates from a local ridge named Federnberg. The Federnberg Schotter is a large remnant of extended gravel accumulations along the rivers north of the Kobernaußer Wald (Rupp 2008).

The base of the gravel is marked by an unconformity at the transition to the Neogene deposits of the Molasse Basin.

The deposit consists of predominantly rounded and well-rounded coarse sand-bearing gravel. It is poorly sorted and more or less horizontally bedded with intensive cross bedding which typifies deposition by a braided river. Petrographically the gravel is dominated by quartz and quartzite. Pebbles of crystalline rocks are rare and limestone pebbels are very rare. The material is frequently eroded consitst largely of re-deposited gravel and sand of the Neogene Hausruck Formation. The gravel is weathered and strongly oxidized.

The chronostratigraphic age is thought to correlate with a cold period in the Early Pleistocene, much older than the period when the Eichwald Schotter were formed.

Langenloiser Terrasse

The first description of the Langenlois terrace was given by Fink & Piffl (1976c) for the type area in the southern part of Kremsfeld (location see Fig. 6; ÖK 1:50,000 sheet 38 Krems a.d. Donau). Synonymous is the term Gobelsburger Terrasse (Piffl 1959).

Lithologically the unit consists of coarse sand-bearing gravel with a thickness ranging from 10 to 15 m. The deposits are unconformably underlain by Neogene sediments of the Molasse Basin.

The gravel deposits are strongly weathered and partly covered with loess. They mainly consists of crystalline rocks (c. 70–80%) mixed with limestone and sandstone (30–20%) in the non-weathered parts, typical for fluvial deposits of the Danube. The unit is covered by thick loess deposits interrupted by paleosols.

According to paleomagnetic measurements the gravel accumulation took place in the upper part of the Matuyama chron in the Early Pleistocene.

Eichwaldschotter

The first recognition is from Graul (1937) as 'Aichberg-Geinberg Verschotterung'. The unit is first defined by Weinberger (1955). The type area is situated NE of the city of Mattighofen (location see Fig. 5) on ÖK 1:50,000 sheet 46 Mattighofen. The name (Eichwald gravel in English) originates from a local field name. The gravel unconformably overlies Neogene sediments of the Molasse Basin.

Lithologically the sediment consists predominantly of rounded and well-rounded coarse sand-bearing gravel beds. The lithological composition of the gravel is quite similar to that of the younger terrace gravel along the rivers Inn and Salzach in front of the terminal moraines of the Salzachgletscher. They were formed by braided river as well. The gravel is strongly weathered and covered by loess.

The chronostratigraphic age is assigned to a cold period older than Günz. Based on the similarity in facies and lithology with the typical fluvioglacial sediments of Middle Pleistocene age (e.g. Ältere Deckenschotter of the Günz glaciation) the Eichwaldschotter may represent the beginning of major Alpine glaciations at MIS 22 during the Early-Middle Pleistocene transition, as recorded in the southern Alpine area and foreland (Muttoni et al. 2003, 2007).

Kiese von Reuharting - Schnelling, Forstholz

Publications of Kohl (in: Krenmayr et al. 1997) and Krenmayr et al. (2006) describe the unit (gravel of Reuharting-Schnelling, Forstholz**)** for the type area in the northern part of the Traun-Enns Platte (locations see Fig. 5; ÖK50 sheets 49 Wels, 51 Steyr).

The lithology of the 20 to 30 meter thick unit consists of coarse sand-bearing gravel deposits. The predominantly occurring sub-rounded crystalline rocks are partly mixed with limestone and dolomites. The gravel is deeply weathered and partly covered with a residual clay deposit. According to sediment structures and some sub-angular boulders the accumulation took place during cold periods (Kohl in: Krenmayr et al. 1997).

The chronostratigraphic age is assumed as cold periods older than Günz (Kohl in Krenmayr et al. 1997) and may correlate with MIS 22 according to arguments mentioned for the Eichwaldschotter unit.

Fig. 8: Outcrop of the Federnberg Schotter (location south of Ried/Innkreis, see Fig. 5) showing horizontally bedded and oxidized gravel with rounded clasts consisting predominantly of quartz and quartzite (outcrop height is approximately 2 m). Layers of clast-supported gravel with open-framework are indicative for deposition by braided river.

Abb. 8: Aufschluss mit Federnberg Schotter (Lokalität südlich von Ried/Innkreis, siehe Abb. 5) bestehend aus horizontal geschichtetem und oxidiertem Schotter mit gerundeten Quarz- und Quarzitgeröllen (die Aufschlusshöhe beträgt etwa 2 m). Lagen von korngestützen Kiesen („Rollkiese") sind typisch für die Ablagerung durch „braided river".

Amstettner Bergland

A description is given by Krenmayr & Schnabel (2002) for the type area in the hills between the rivers Enns, Donau and Ybbs (location see Fig. 5; ÖK 1:50,000 sheets 51 Steyr, 52 St.Peter i. d. Au, 53 Amstetten) near the city of Amstetten. Synonyms are Strengberg Schlierriedelland and Ybbs-Erlauf-Melk Schlierriedelland (Fischer 1979).

The lithology of the up to 20 m thick unit consists of fine to coarse sand and clay containing gravel deposits. The gravel is strongly weathered and covered by weathered loess. This gravel deposits is interpreted as the remnant of former terraces accumulations formed by the river Danube. The gravel mainly consists of crystalline rocks, mixed with limestone and sandstone components supplied by the southern tributaries of the Danube. In the highest elevated terrace these materials are mostly weathered while in the lower situated terraces 30 to 40% of the sediment is unweathered.

The chronostratigraphic age is assumed to correlate with Early Pleistocene.

Maria Ellender / Arbesthaler Hügelland

Schnabel et al. (2002) mentioned the unit in the type area which is the hilly area (the meaning of Hügelland in German) south of the river Danube (location see Fig. 6) between Königsberg in the West and Wartberg in the East (ÖK 1:50,000 sheet 60 Bruck a.d. Leitha).

The unit is made up of remnants of former extended gravel deposits. It consists of fine to coarse sand-bearing gravel beds interbedded with up to 20 m thick sand layers. The gravel clasts are mainly rounded to well-rounded and composed of c.80–90% crystalline rocks mixed with limestone and sandstone. The sedimentology indicates a deposition by the river Danube. The chemical weathering of the deposits is very well developed and reaches down to the base of the gravel.

The chronostratigraphic age is correlated with the Early Pleistocene (Fuchs 1985c).

Rauchenwarter Platte

The unit was first described by Küpper (1968). The type area is the hilly area between the Vienna Airport (Katharinenhof) in the north and the villages of Himberg and Ebergassing in the south (ÖK 59 Wien). The name [(gravel) sheet of Rauchenwarth in English] is derived from the village of Rauchenwarth (location see Fig. 6).

Lithologically the unit consists of fine to coarse sand-bearing gravel deposits interbedded with sand layers. The deposit is interpreted as the remnants of former extended gravel deposits. The gravel is mainly rounded to well-rounded and composed of 80–90% crystalline rocks mixed with some limestone and sandstone indicating deposition by the river Danube. The chemical weathering of the deposits is intensive and may reached down to the base of the gravel. North of Rauchenwarth the gravel and Neogene sediments, which make up the base of the gravel, are covered by loess (Fuchs 1985). The thickness of the the unit amounts some 15 m.

The chronostratigraphic age of the deposits are correlated with the Early Pleistocene (Fuchs 1985 d).

Laaerberg Terrasse

This unit (Laaerberg terrace in English) was first defined by Schaffer (1902) and later on described by Fink & Majdan (1954) and Küpper (1968) for the type area in the 10th district of the city of Vienna (see Fig. 7) around the flat hill called Laaerberg (ÖK 1:50,000 sheet 59 Wien) a recreation area.

Lithologically it consists of coarse sand-bearing gravel of crystalline rocks (mostly quartz and quarztite) which was deposited by the river Danube. The unit shows an unconformable contact to underlying Neogene sediments and has a thickness around 3–4 m. The gravel deposits have a reddish matrix as a result of intense weathering and show cryoturbation structures.

The chronostratigraphic age is older than that of the Günz glaciation and is assumed to correspond with cold periods within the Early Pleistocene.

Middle Pleistocene Units

Günz-Moräne (terminal moraine, basal till)

The first description of Günz-Moräne in the sense of terminal moraine was given by Penck & Brückner (1909) for the type area in the Iller-Lech Platte, along the river Günz. Reference sections in Austria are described by Weinberger (1955) and Kohl (2000). In Austria the Günz moraines of the Salzach glacier are well developed at Siedelberg (Weinberger 1955) west of Uttendorf (location see Fig. 5), where also the transition into the gravel of the Ältere Deckenschotter is preserved. Other remnants of these terminal moraines are described from the Traun glacier at Berg SE Lindach and from the Krems glacier around Sattledt (Weinberger 1955, Kohl 2000, Egger & van Husen 2007).

Lithologically the unit consists of diamictons (till) of coarse sand-bearing gravel with boulders. Often a varying content of silt and clay can be noticed. Locally indistinct bedding can be found. The clast composition of the deposits reflects the lithology in the catchment area according to the resistance of the material against glacial abrasion. Only the remnants of basal till on the up-flow side of the terminal moraine are highly consolidated (compare Fig. 1). The till is normally deeply weathered to depths of 5 meter. The thickness of the unit is unknown and probably shows strong variations. The unit is partly covered by loess.

The Günz basal till, consists of an overconsolidated massive, matrix-supported diamicton. It has an unconformable contact to underlaying pre-Quaternary bedrock as well as older Pleistocene sediments.

Genetically, the Günz terminal moraine was deposited (overwhelmingly) as a dump moraine by a stationary glacier. It marks the maximum ice extent of the glacier tongues menitioned above. Generally, the basal till can be classified as a subglacial traction till (Evans et al. 2006).

The chronostratigraphic age is probably correlated with MIS 16 (van Husen 2000a).

Älterer Deckenschotter

This unit was first described by Penck & Brückner (1909) for the type area in the Iller-Lech Platte. The name meaning older sheet of gravel in English originates from the morphologically wide-spread occurrence of the apparently homogenuous gravel deposits north of the Eastern Alps, like in the Traun-Enns Platte. Synonymous are the Terrasse N Hochstraßburg (Fuchs 1964) and the Enns-Ybbs Schotterplatte (Fischer 1979).

The lithology shows coarse sand-bearing gravel typified by a poor sorting and bedding. The lithology of the clasts corresponds to the sources in the catchment areas of the rivers. Along the rivers Traun and at the Traun-Enns Platte (between the rivers Traun and Enns, Fig. 5) the material predominantly derived from the Alps (limestone, dolomite, and flysch sandstones) is mixed with older crystalline-bearing gravel in the lower part of the sequence (Kohl 2000). At Enns-Ybbs Schotterplatte (between the rivers Enns and Ybbs, Fig. 5) the gravel was supplied by the river Enns (Fischer 1979). Distinct gravel layers may show a good cementation.

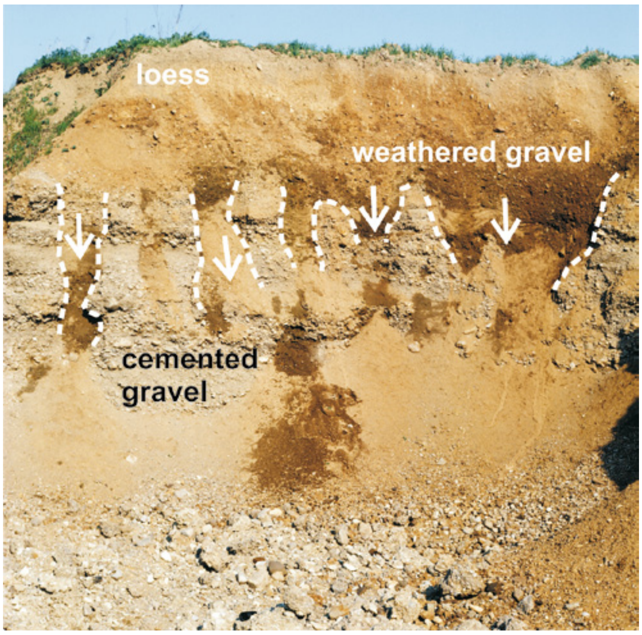

Fig. 9: Outcrop of Ältere Deckenschotter (location east of Kremsmünster) with a cover of younger loess on top (outcrop height approximately 6 m). White arrows and dashed lines indicate the locations of pipe-like weathering structures ("Geologische Orgeln") which occur between "pillars" of cemented gravel (conglomerate).

Abb. 9: Aufschluss mit Älterem Deckenschotter (Lokalität östlich von Kremsmünster), der von einem jüngeren Löss bedeckt ist. Die weißen Pfeile und die strichlierten Linien zeigen die Lage von röhrenförmigen Verwitterungsstrukturen („Geologische Orgeln") zwischen konglomerierten Kiesen an.

Intensive weathering is evident on the top of the gravel below the up to 10 m thick loess cover. Frequently occurring pipe-like weathering features (Geologische Orgeln) exsist throughout the whole sequence (see Figs. 2 & 9). The unit has a variable thickness of 15 to 30 meter due to changing bedrock topography. It consists of fluvial gravel mainly deposited by braided rivers. The unit is connected with terminal moraines in the Salzach glacier at Siedelberg West of Uttendorf (Weinberger 1955), in the Traun-Enns Platte (Kohl 2000), and the Enns-Ybbs Schotterplatte (Fischer 1979). Some remnants occur along the Danube and its southern tributaries (Krenmayr & Schnabel et al. 2006, Schnabel et al. 2002).

The chronostratigraphic age is probably correlated with MIS 16 (van Husen 2000a), but the unit may include older deposits as well.

Wienerberg Terrasse

This unit (in English: Wienerberg terrace) was first described by Fink & Majdan (1954) and Küpper (1968) for the type area in the 10th district of the city of Vienna (see Fig. 7) around Spinnerin am Kreuz (ÖK 1:50,000 sheet 59 Wien). Lithologically it consists of coarse sand-bearing gravel of mainly crystalline rocks which were deposited by the river Danube. The thickness amounts 10 m. In the upper parts subangular flysch gravel (Plattelschotter) frequently occurs. The gravel deposits are weathered in the upper part and covered by loess. Cryoturbations mixed both. Remnants of elephants (El. planifrons) were found by Küpper (1968).

It is supposed that the unit represents the Älteren Deckenschotter in the Vienna Basin. Thus the chronostratigraphic age is assumed to correlate as well to MIS 16.

Prellenkirchner Terrasse

The unit was mentioned by Wessely (2006) as Petronell-Prellenkirchner Terrasse with the type area around the village of Prellenkirchen (ÖK 1:50,000 sheets 61 Hainburg, 79 Neusiedl a. See). The name (in English: Prellenkirchen terrace) derives from the village of Prellenkirchen (location see Fig. 6).

The terrace consists of coarse gravel and sand deposited by the river Danube. The gravel is rounded to well-rounded and consists predominantly of crystalline rocks (c. 80%) mixed with limestone, dolomite and sandstones (c. 20%). It is strongly weathered and partly covered with loess. The gravel deposit is underlain by a basal package of sand and clay. It is situated at about 40 m above the recent levels of the rivers Danube and Leitha. Sediment structures (e.g. cross bedding) indicate deposition by braided rivers. The thickness is about 10 m.

The unit developed during probably two glacial periods (Günz, Mindel, cf. Fuchs 1985b). Thus the chronostratigraphic age might correlate with MIS 12 and MIS 16.

Parndorfer Platte

Descriptions of this unit are from Wessely (1961) and Häusler (2007) for the type area east of Parndorf (ÖK50 sheets 61 Hainburg, 79 Neusiedl a. See). The name meaning (gravel) sheet of Parndorf in English originates from the village of Parndorf (location Fig. 6).

Lithologically the unit consists of fine to coarse sand-bearing gravel deposits of the river Danube. The gravel clasts are rounded to well rounded and predominantly composed of crystalline rocks (c. 90%) mixed with limestone, dolomite and sandstones (c.10%) in the lower situated younger parts. The older, higher situated gravel, which is strongly weathered and partly covered with loess deposits shows intensive cryoturbation (Häusler 2007). Gravel deposits occur tectonically isolated from its surroundings at an about 20 m higher situated base of sand and clay (Fuchs 1985). Sediment structures (e.g. cross bedding) indicate deposition by a braided river. The thickness is about 10 m.

It is assumed that the sediments were deposited during two glacial periods (Günz, Mindel, cf. Fuchs 1985a, b; Häusler 2007). Thus the chronostratigraphic age might correlate with MIS 12 and MIS 16.

Kaiserwaldterrasse

The first descriptions was given by Penck & Brückner (1909). Additional information is provided by Winkler-Hermaden (1955) and Fink (1961). The type area of the Kaiserwald terrace is south of Graz (location see Fig. 4) between the rivers Mur and Kainach (ÖK 1:50,000 sheet 190 Leibnitz).

Lithologically the unit consists of coarse sand-bearing gravel deposits which show intensive cross bedding. The material was deposited by the rivers Mur and Kainach. The base of Kaiserwaldterrasse showing an unconformable contact to Neogene sediments is above the surface level of the Grazer Feld (Niederterrasse) surface. An up to 10 m thick cover of weathered loess is characteristic for this up to 15 m thick gravel unit (Ebner 1983).

The chronostratigraphic age is according to the high baselevel and the loess cover probably correlated with the Günz glaciation (MIS 16) but the unit may include older deposits as well.

Weiße Nagelfluh

The first description was given by Angerer (1909) for the type area in the Traun-Enns Platte (ÖK 1:50,000 sheets 67 Grünau i. Almtal, 68 Kirchdorf) with the type section in the former quarries Lärchwand (N 48°03'20", E 14°07'15") and Wolfgangstein (N 48°04'00", E 14°08'48") both located in the village of Kremsmünster (location see Fig. 5). A reference section is in the quarry of Egenstein (N 47°58'42", E 13°57'35"). The name (in English: white conglomerate) derives from the striking bright colour of the conglomerates. Synonym is the Kremsmünsterer Nagelfluh.

Lithologically the deposit is made up of massive well cemented sand-bearing conglomerates (Figs. 10 & 11). The clasts are predominantly rounded limestone, dolomite and some sandstone (Flysch).

The deposit is 5 to 15 m thick. Angular to sub-angular boulders probably transported by ice floes occur frequently. The sediments are poorly sorted with intensive cross bedding and small foresets (channel fill). The uppermost part shows weathering with layers of reddish clay (Kohl in Krenmayr et al. 1997, Fig. 11). The deposits is well-known as local building stone. The unit was probably deposited by braided river very likely during a cold period. A connection with till deposits is not known.

The chronostratigraphic age is probably correlated with MIS 14 (van Husen 2000a).

Mindel-Moräne (terminal moraine, basal till) and Vorstoßsedimente

The first description of Mindel-Moräne in the sense of terminal moraine was given by Penck & Brückner (1909). In Austria, Weinberger (1955), del Negro (1969) and Kohl (2000) mentioned the unit. Type area is the Iller-Lech Platte, along the river Mindel. Reference sections in Austria are situated only at the northern rim of the Eastern Alps where the glacier termini during the Mindel glacial are well documented like in the area between the Salzach glacier in the West and the Krems glacier in the East (Weinberger 1955; del Negro 1969; Kohl 2000, Egger & van Husen 2003; van Husen 1989; Egger 1996; Egger & van Husen 2007). The ridge of Sperledt between Adenberg and Edt (Weinberger 1955) marks the terminal moraine of the Salzach glacier. The same is true for the Traun glacier at Forstern, Pondorf, Weißenkirchen, Pfaffing, Hehenberg and Laakirchen, Rabesberg (Weinberger 1955, del Negro 1969, Kohl 2000, Egger & van Husen 2007) and for the Krems glacier at Magdalenerberg, Kremsmünster and Schlierbach (Weinberger 1955, Kohl 2000, Egger & van Husen 2007, Fig. 5).

Lithologically the unit consists of diamictons (till) of coarse sand-bearing gravel with boulders. Often a varying content of silt and clay can be noticed. Locally indistinct

Fig. 10: Historical quarry in Kremsmünster to mine the building stone of Weiße Nagelfluh (white conglomerate) (location s. Fig. 5). The superposition of Weiße Nagelfluh(white conglomerate made up predominantly by triassic limestone) by Graue Nagelfluh, a conglomerate representing the proglacial sediments of the advancing Krems-Steyr glacier during the Mindel glaciation and finally by the Mindel basal till is evident.

Abb. 10: Historischer Steinbruch in Kremsmünster (Lage s. Abb. 5) für den Abbau der als Baustein genützten Weißen Nagelfluh. Dieses aus hellen Karbonatgeröllen bestehende Konglomerat wird von Grauer Nagelfluh („Vorstoßschotter" der Mindel-Vergletscherung) und letztlich der Mindel-Grundmoräne überlagert.

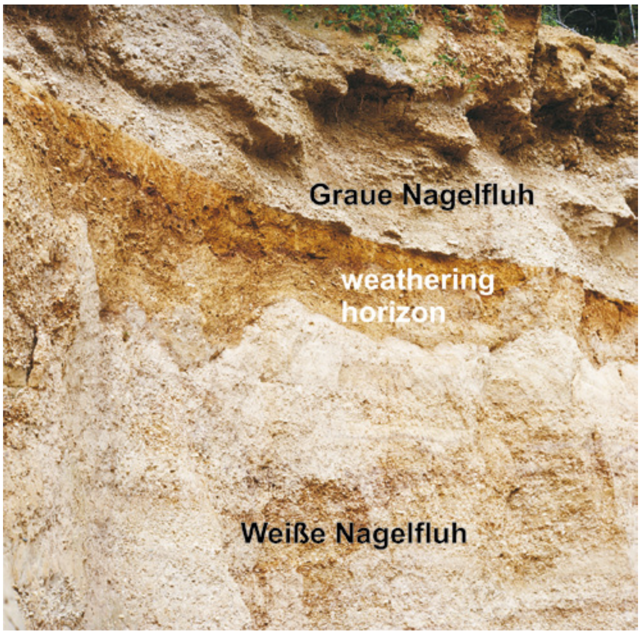

Fig. 11: Weathering horizon on top of Weiße Nagelfluh (white conglomerate) overlain by Graue Nagelfluh (grey conglomerate) indicating a stable surface under supposed interglacial conditions (location: quarry south of Kremsmünster, height of the outcrop approximately 4 m).

Abb. 11: Der Verwitterungshorizont am Top der Weißen Nagelfluh und überlagert von Grauer Nagelfluh dokumentiert vermutlich interglaziale Bedingungen (Lokalität: Steinbruch südlich von Kremsmünster, Aufschlusshöhe ca. 4 m).

bedding can be found. The clast composition of the gravel deposits reflects the lithology in the catchment area according to the resistance of the material against glacial abrasion. Only the remnants of basal till on the up-flow side of the terminal moraine are highly consolidated (see Fig. 1). The till is normally deeply weathered to an average depth of 3–5 meter. The thickness ranges from some meters to 30–40 m. The unit is partly covered by loess.

The Mindel basal till, consisting of massive, matrix-supported diamicton, often covers a few meter thick basal gravel bed which reflects sedimentary transition to the till. These gravel deposits called "Vorstoßschotter" in German were formed in front by fluvial action in of the advancing glacier and covered by till immediately after deposition (Fig. 1 & Fig. 9).

Genetically, the Mindel terminal moraine was (overwhelmingly) deposited as a dump moraine by a stationary glacier. It marks the maximum ice extent of the tongues of Salzach, Traun and Krems glacier (Weinberger 1955, Kohl 2000, van Husen 1977, Egger & van Husen 2007) during the pleniglacial conditions.

Riß basal till (German: Grundmoräne) i.e. overconsolidated massive matrix-supported diamicton with occasional shear planes) occurs on top of pre-Quaternary bedrock as well as on older Pleistocene sediments. The contact is in most cases unconformable. Generally, the basal till can be classified as a subglacial traction till (Evans et al. 2006).

The chronostratigraphic age is probably correlated with MIS 12 (van Husen 2000a).

Graue Nagelfluh

The first description is from Kohl (1977) for the type area around Kremsmünster (ÖK50 sheet 68 Kirchdorf, location see Fig. 6). The the type section is situated in the quarry Lärchwand (N 48°03'20", E 14°07'15"). The name (English meaning: gray conglomerate) originates from the dark greyish colour that results from a high content of Flysch sandstones.

The lithology of the 5–10 m thick unit is described as coarse sand-bearing gravel with a weak bedding. Clasts consist of limestone, dolomite and sandstone and are irregularly cemented. Frequent cross bedding and a transition into the overlying till (Mindel) is evident. The unit was probably deposited by a braided river in front of the advancing glacier (Mindel) in the Krems valley (Upper Austria) around Aiterbach, Rindbach, Kremstal (Kohl 2000). The underlying unit is the weathered Weiße Nagelfluh.

The chronostratigraphic age is probably correlated with MIS 12 (van Husen 2000a).

Jüngerer Deckenschotter

Description was given by Penck & Brückner (1909) especially for the Iller-Lechplatte. The name meaning younger sheet of gravel in English indicates the unit as a morphologically wide-spread gravel deposit which is only slightly incised into the Älterer Deckenschotter (Fig. 2), like in the Traun-Enns Platte (between the rivers Traun and Enns, Fig. 5). Synonymous are the Terrasse von Lehen and respectively the Terrasse S Ordning (Fuchs 1964).

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The lithology consists of coarse sand-bearing gravel deposits with weak layering. The material reflects the lithology of the catchment areas of the supplying rivers. In contrast to the Älteren Deckenschotter along the rivers Traun and Enns, all the material of the Jüngerer Deckenschotter originates from the Alps as is demonstrated by the content of limestone, dolomite, and flysch sandstone. In some layers the gravel is well cemented. The gravel deposits are intensively weathered at the top which is covered by loess. Pipe-like weathering features (Geologische Orgeln) occur frequently (s. Fig. 2).

The unit is up to 40 m thick and connected to Mindel Moränen NE of Adenberg (Weinberger 1955), S Lindach (Kohl 2000, Egger & van Husen 2007). Additional remnants Jüngerer Deckenschotter occur along the Danube and its southern tributaries (Krenmayr & Schnabel et al. 2006, Schnabel et al. 2002).

The chronostratigraphic age is probably correlated with MIS 12 (van Husen 2000a).

Mönchsberg Nagelfluh

The first descriptions of the Mönchsberg conglomerate were given by Boué (1830), Morlot (1847), Penck & Brückner (1909), and Götzinger (1936). The type area is the city of Salzburg (location see Fig. 5) and its vicinity (ÖK 1:50,000 sheet 63 Salzburg). The type section is located at the Mönchsberg (N 47°48'00" E 13°02'00") in the city center of Salzburg of which the name of the unit is derived. Synonymous the term Salzburger Nagelfluh is used.

Lithologically the unit consists of coarse sand-bearing gravel deposits which are in part well-cemented to conglomerate. The outcropping thickness reaches 80 m. The gravel composition is similar to that of the modern gravel of the river Salzach. Layers are dipping 20°–30° in west to northeastern directions. Apart from a few layers that consist only of coarse gravel without sand the conglomerates show a predominantly sand matrix. The conglomerates are well-known for its use as building stone (Kieslinger 1964). The unit is supposed to represent foreset-beds of a kame which was formed in small lakes during the initial phase of down-melting of the Salzach glacier at the end of the Mindel glaciation (Termination V).

Thus the unit is probably correlated with MIS 12 (van Husen 2000a).

Arsenal Terrasse

Publications about the unit called Arsenal terrace in English are from Schaffer (1902), Fink & Maydan (1954), and Küpper (1968). The type area is the railway station "Südbahnhof" and the nearby situated former military complex Arsenal (location see Fig. 7; ÖK 1:50,000 sheet 59 Wien).

Lithologically the unit consits of 10–15 m thick coarse sand-bearing gravel deposits. The gravel is mainly composed of crystalline rocks from the river Danube and contains angular boulders (Suess 1862) in the lower parts which were obviously transported by ice floes. In the upper parts layers with subangular flysch gravel (Plattelschotter) are dominant. The gravel deposits are covered by a weathering zone and loess which are intermingled by cryoturbations.

It is supposed that the unit represents the Jüngeren Deckenschotter in the Vienna Basin. Thus the chronostratigraphic age is assumed to correlate as well with MIS 12.

Höttinger Brekzie

The first recognition of the Hötting breccia was made by Escher von der Linth (1845) and Morlot (1847). Modern comprehensive descriptions are given by Penck 1921 and Sanders & Ostermann (2006). The type area is in Innsbruck (Fig. 1) north of the river Inn between Höttinger- (N47°17'00" E 11°22'20") and Mühlauergraben (N 47°18'00" E 11°24'50") (Fig. 1; ÖK 1:50,000 sheet 118 Innsbruck). The name comes from the village of Hötting (now part of Innsbruck) at the mouth of the Höttingergraben. Synonymous are other similar breccias on the southern rim of the Calcareous Alps (van Husen 2000a).

The lithology is a well-cemented breccia containing angular triassic carbonate rocks, silt-sandstone and some associated crystalline erratics. The predominantly coarse talus contains some fine-grained layers. Based on the colour two types of breccias can be recognized: the White Breccia and the Red Breccia in the lower parts of the slope. The colour results from the bedrock colour that influences the matrix (Ampferer 1936). Plant fossils crop out on one spot (Rossfall-Lahner N 47°17'30" E 11°22'40"). The flora is rich in taxa indicating warm interglacial conditions (e.g. Rhododendron, vitis) during deposition (v. Ettingshausen 1885, v. Wettstein 1892, Gams 1936, Denk 2006).

The origin and facies of the unit is a talus formed mostly by debris and mud flows but also by rock fall and grain flow (Sanders, Ostermann & Kramers 2009). The latter formed laminated silt deposits in distal puddles (Sanders & Ostermann 2006). The thickness can amount more than 100 m. The unit is underlain by older till (Mindel) and Triassic bedrock and superimposed by two tills separated by gravel deposits (Ampferer 1936).

The chronostratigraphic age is supposed to Mindel/Riß interglacial (Penck 1921, Ampferer 1936) and can probably cover the full time-span of MIS 11 to MIS 7 (van Husen 2000a). Recently a correlation with MIS 5 is discussed (Sanders & Ostermann 2006). Such a young age is supported by luminescence ages which suggest an Early- to Middle Würm deposition of the Hötting Breccia (Gemmel & Spötl 2009).

Riß-Moräne (terminal moraine, basal till) and "Vorstoßsedimente"

The first description of Riß-Moräne in the sense of a terminal moraine (German: Endmoräne) was given by Penck & Brückner (1909). The type area is located at the eastern rim of the former Rhein glacier around the type locality Biberach a. d. Riß. Reference areas are in the Salzach glacier (Weinberger 1955) and Traun glacier (van Husen 1977) area. The name is derived from the River Riß (Baden Württemberg /Germany).

Only few clear remnants of Riss terminal moraines are known in the Eastern Alps: Salzach glacier (locations see Fig 2) around Thann, Grund, Gilgenberg, Hinterklam (Weinberger 1955) and Kühberg (Egger & van Husen

2003), Traun glacier around the glacier tongues at Irrsee, Attersee and Traunsee (Egger & van Husen 2003, van Husen 1989, Egger 1996, Egger & van Husen 2007), and Krems glacier around Warthberg (Kohl 2000).

Lithologically the unit consists of diamictons (till) of coarse sand-bearing gravel with boulders. Often a varying content of silt and clay can be noticed. Locally indistinct bedding can be found. The clast composition of the gravel deposits reflects the lithology in the catchment area according to the resistance of the material against glacial abrasion. Only the remnants of basal till on the up-flow side of the terminal moraine are highly consolidated (see Fig. 1). The till shows normally advanced weathering, averaging a depth of 1 to 2 m. The thickness ranges from some meters to 30–50 m. The unit is partly covered by loess.

The Riß basal till often covers a few meter thick basal gravel bed which reflects sedimentary transition to the till. These fluvial gravel deposits called "Vorstoßschotter" in German were formed in front of the advancing glacier and covered by till immediately after deposition.

Genetically, the Riß terminal moraine was (predominatly) deposited as a dump moraine by a stationary glacier. It marks the maximum ice extent of the tongues of Salzach, Traun and Krems glacier (Weinberger 1955, Kohl 2000, van Husen 1977, Egger & van Husen 2007) during the penultimate pleniglacial conditions.

Riß basal till (German: Grundmoräne) i.e. overconsolidated matrix-supported massive diamicton with occasional shear planes) occurs on top of pre-Quaternary bedrock as well as on older Pleistocene sediments. The contact is in most cases unconformable. Generally, the basal till can be classified as a subglacial traction till (Evans et al. 2006).

The chronostratigraphic age of the unit is correlated with MIS 6 (van Husen 2000a). Such an assumption is backed by findings at Mondsee (van Husen 2000c; see Mondsee Deltakomplex) where in a continuous sequence Riss basal till is superimposed by Riss/Würm interglacial lake deposits (Drescher-Schneider 2000), correlated with the Eemian; MIS 5e).

Hochterrasse

The term meaning high terrace in English was introduced by Penck during geological mapping in the Bavarian Alpine Foreland (Geologische Karte Ingolstadt). The type area was first around Ingolstadt and later in the Iller-Lech-Platte. Originally the name was connected with the large terrace on the valley flanks that follows the modern river course. Later it was considered to be the melt water accumulation of the penultimate glacial cycle (Penck & Brückner 1909).

In the area of the Vienna Basin (surrounding the city of Vienna, Fig. 6) the Terrasse westlich Seyring (Grill 1951), the Gänserndorfer Terrasse (Fink 1954), the Theresianumterrasse (Küpper 1968), the Stadtterrasse, and the Simmeringer Terrasse (Schaffer 1902) are synonyms.

The terrace deposits consist of coarse, sand-bearing gravel with weak bedding. Gravel composition displays the lithology of the catchment area of the respective rivers. Along the Danube material from the Alps in the south (e. g. limestone, dolomite, flysch, sandstones) is mixed with the gravel from the tributaries originating in the Bohemian Massif. The thickness of the deposits varies between 20 and 50 m. The gravel deposits show only locally weak cementation. Well-developed weathering occurs on the top just below the loess cover. The onset of pipe-like weathering (Geologische Orgeln) can locally be recognized.

The fluvial gravel deposits were mainly accumulated by braided rivers which were directly connected to the Riß terminal moraines of the Salzach glacier at Gilgenberg (Weinberger 1955; Fig. 5) and of the Traun glacier at Lenzing, Schörfling and Gschwandt (Egger 1996, Egger & van Husen 2007). Some remnants of the unit occur in non-glaciated valleys without terminal moraines. Extended units of Hochterrasse are present along the Danube and its southern tributaries (Krenmayr & Schnabel 2006, Schnabel et al. 2002).

The Hochterrasse of the Inn valley at Gunderding has been dated by optically stimulated lumescence (OSL) providing deposition ages between ~200 and 140 ka (Megies 2006). Such a result is supported by an U/Th dating of a calcitic cement from the same gravel pit providing a minimum age of 113.4 ± 4.4 ka (Terhorst, Frechen & Reitner 2003) of the deposit. The chronostratigraphic age is therefore correlated with MIS 6.

Torrener Nagelfluh

The first description of this Torren conglomerate is given by Pippan (1957) and Kieslinger (1964) for the type area in the Salzachtal around Golling (Fig. 5; ÖK 1:50,000 sheet 94 Hallein). The type section is situated in a quarry at Torren (N 47°35'50", E 13°09'10") which is the name-giving village.

The lithology of the unit is typified by partly well-cemented sand-bearing gravel. The deposit is dominated by carbonate pebbles from local sources which are mixed with crystalline clasts. Only a few layers show well-developed cementation, which were used for building stone (Kieslinger 1964). Layers with clay coating of the pebbles are poorly cemented. The lower sediment layers of the sequence show clinoforms with a dip of 30° to the North. The upper part shows horizontal layering with cross bedding. The uppermost part (c. 2 m) is in part intensively weathered. The sequence is probably formed as a delta complex with fore and top sets in a lake between stagnant ice and the slope (kame terrace).

The outcropping part of the unit has a thickness of about 30 m. A conformable transition to lower situated bottom sets consisting of banded clay is assumed.

The chronostratigraphic age assumes an origin during the initial phase of down-melting at the end of the Riß glaciation. Thus it is correlated with Termination II and with MIS 6 (van Husen 2000a).

Stadtterrasse

Descriptions of the unit were given by several authors (Schaffer 1902; Fink & Majdan 1954; Küpper 1968; Fink 1973). The type area is in the center of the city of Vienna (see Fig. 7; old city around St. Stephen's cathedral, today 1st district – ÖK 1:50,000 sheet 59 Wien). The name meaning city terrace is from the old city of Vienna. Simmeringer Terrasse (Schaffer 1902) and Theresianumterrasse (Küpper 1968) are synonymous.

Lithologically the unit consists of coarse gravel deposits with sand and shows weak layering. The gravel is rounded to well-rounded and is composed of c. 80% crystalline rocks, c. 20% pebbles of limestone and flysch sandstone. The material was deposited by the Danube. Angular boulders of 1 m and more in diameter are mainly found in the lower part of the deposit (Küpper 1950). They were transported and deposited by ice floes during glacial climatic conditions. At the mouth of tributaries originating from the Vienna Woods thick layers of predominant subangular flysch material ("Plattelschotter") interdigitate with the Danube terrace deposits (Küpper 1968, Fink 1973). The terrace is covered with loess and was mainly accumulated by braided rivers. The thickness amounts 10 to 15 m.

It is supposed that the unit represents the Hochterrasse in the Vienna Basin south of the Danube. Thus the chronostratigraphic age is assumed to correlate as well with MIS 6.

Gänserndorfer Terrasse

The first description of the Gänserndorf terrace was given by Fink & Majdan (1954). The type area is the Vienna Basin North of the river Danube (ÖK 1:50,000 sheets 41 Deutsch Wagram, 42 Gänserndorf). The name originates from the city of Gänserndorf (location see Fig. 6). The terrace W of Seyring is synonymous.

Lithologically the unit consists of coarse sand-bearing gravel that show weak layering as well as some cross-bedding.

The gravel was deposited by the river Danube. It is made up of rounded to well-rounded clasts which consist of about 80% crystalline rocks and about 20% limestone and flysch-sandstone. The uppermost part of the unit is weathered and shows strong oxidation of iron (hydroxides). The upper 3 to 4 m of the unit was affected by ice wedges and intensive cryoturbation which included also soil and loess material. In part the terrace body is tectonically subsided at Aderklaa, Obersiebenbrunn, and Lassee (Fuchs & Grill 1984, Decker, Peresson & Hinsch 2005). The fluvial gravel is 10 to 15 m thick and was mainly accumulated by braided rivers.

It is supposed that the unit represents the Hochterrasse in the Vienna Basin north of the Danube. Thus the chronostratigraphic age is assumed to correlate as well with MIS 6.

Late Pleistocene Units

Deltakomplex Mondsee

The first description of the 'Mondsee-Interglazial' was given by Klaus (1975, 1987) and Kohl (2000). Detailed investigations were carried out during 1992–1996 (van Husen 2000b). The type area is the slope north of the village of Mondsee (Fig. 5) near the farmhouse Steiner (N 47°51'56" E 13°20'48" – ÖK 1:50,000 sheet 65 Mondsee). The type section is the Steinerbach (N 47°51'54" E 13°20'37") and three drillholes (N 47°51'54", 55", 56" E 13°20'38", 39", 40"). The name denoting complex delta deposits of Mondsee in English originates from the village of Mondsee.

Lithologically the unit superposes an older till (Riß). The sequence starts with laminated clay, silt and lake marls,

Fig. 12: Riß/Würm - Interglacial (Eemian) lacustrine sediments (lake marl and banded clay) at Mondsee. White sheets mark different pollenzones.

Abb. 12: Lakustrine Ablagerungen (Seekreide und Bänderschluff) aus dem Riß/Würm - Interglazial (Eem).

which were deposited during the interglacial period (Eemian). This lower part is overlain by a coarsening upward sequence of clay, silt and sand layers (Krenmayr 2000). The whole package is covered by basal till (Late Würm).The unit is rich in pollen which document the vegetation development from the late glacial period of the Riß (Termination II, MIS 6) to Middle Würm (MIS 3) (Drescher-Schneider 2000). The pollen record is completed by many macro plant macro remains (Oeggl & Unterfrauner 2000). The preserved sequence evolved as a Gilbert type delta with bottom, fore, and top sets deposited in an ancient greater Lake Mondsee with a lake level of about 60 m above the present-day lake-level (van Husen 2000c). The deposits show a thickness of 10–35 m. The chronostratigraphic age of the sequence is correlated with MIS 6 to 3.

Nieselach deposits

The deposits are described by Fritz (1971), van Husen & Draxler (1982), van Husen (2000a). The type area is situated south of St. Stefan in the Gail valley (ÖK 1:50,000 sheet 199 Hermagor, Fig 4). The village Nieselach is name-giving.

The about 1.5–2 m thick lignite (Fig. 13) as a part of the sediment sequence was repeatedly the base of mining activities, Ucik (1973).

The 6–8 m thick sequence consisting of horizontally bedded sandy, silty, occasionally gravelly sediments with lignite in the uppermost part conformably overlays banded clay (lake deposits after Riß deglaciation). The lignite is unconformably overlain by coarse gravel, which is regarded to represent "Vorstoßschotter" i.e. proglacial fluvial sediments deposited during the glacier advance phase of the Late Würm glaciation.

The predominantly coarse sand layers with gravel and silt layers were deposited in a meandering river with a low-en-

Fig. 13: Outcrop at Nieselach showing the lignite overlain by the gravel of the "Vorstoßschotter".

Abb. 13: Aufschluss bei Nieselach mit dem Lignit überlagert von „Vorstoßschotter".

ergy stream regime. Layers of massive or banded clay document sedimentation in oxbow lakes, which finally got filled with wood (willows and other bushes) and peat, the source material of the lignite.

According to paleomagnetic data (presence of the Blake event within the sequence) a chronostratigraphic age of MIS 5e is given. However, a U/Th dating of the lignite (113,000 ± 2000 BP; Geyh, Hennig & Oezen 1997) and the palynological record provide arguments for a correlation with the Eemian (MIS 5e) as well as with the 1st Würm Interstadial (MIS 5c). Deposits with a quite similar pollen content are found in fine-grained lacustrine sediments at Freibachtal (SE of Klagenfurt, Carinthia, Fig. 4, Felber & van Husen 1976, Fritz 1992).

Kitzbüheler Terrasse

The unit Kitzbühel terrace was first described by Unger (1836) and mapped by Ohnesorge (1917). Its type locality is in the town of Kitzbühel (Tyrol, Fig. 4), which is namegiving.

Drilhole data for a tunnel and outcrops show a 40 m thick sequence. It consists of a basal till (attributed to MIS 6) overlain by massive and banded silts with no pollen which show a coarsening-upward into sand-bearing gravel deposits (Reitner & Draxler 2002; Reitner 2005). The gravel is overlain by a laminated organic-bearing clayey silt deposit and a three meter thick lignite (a former peat). The latter unconformably underlies the upper basal till (Late Würm, MIS 2).

The coarsening-upward sequence is regarded to represent a phase of rapid sedimentation during or shortly after deglaciation. From the organic-bearing upper part of this and other locations with wood remnants or lignite within the extensive Kitzbühel terrace it is concluded that during an interstadial phase an elevated valley floor with prograding alluvial fans and swampy intercone deposits existed.

Pollenanalyses (by S. Bortenschlager and I. Draxler) together with an U/Th age of 90±8 ka (Reitner 2005) indicate that the peat was formed during the 1st Early Würm Interstadial (MIS 5c). Thus the valley infill of the Kitzbüheler Terrasse supposedly covers the timespan from end of the Riß glaciation (Termination II, MIS 6) to the Early Würm.

A quite similar situation with sediments of EarlyWürm age consisting of lignites intercalated in up to 100 m thick gravel beds are found in the area of Hopfgarten/Brixental (west of Kitzbühel, Fig. 4). The whole sequence is probably correlated with MIS 5d–5a based on palynological evidence (Reitner 2005, Reitner & Draxler 2002).

Würm-Moräne (terminal moraine, basal till) and "Vorstoßsedimente" (e.g. banded-clay deposit of Baumkirchen

The first description of Würm-Moräne in the sense of a terminal moraine was given by Penck & Brückner (1909). The type area is the Lake Starnberg (German: Starnberger See, former Lake Würm/Würm See) and its outlet the river Würm located SE of Munich (Bavaria/Germany, Fig. 4). Reference area is the Austrian lake Traun See and its surrounding (located near the city of Gmunden, Fig. 5) (van Husen 1977). The name originates from the Lake Würm and river Würm. Deposits of the Würm-Moräne occur in all formerly glaciated valleys of the Eastern Alps. Prominent examples of Würm-Moräne are located in the surrounding of the Salzach Valley N of Salzburg and as well in the Drau valley east of Klagenfurt (see glacier extent in Figs. 4, 5)

Lithologically the Würm terminal moraine unit consists of in general massive diamicton (till), of coarse-grained sand-bearing gravel with boulders and an often varying content of silt and clay. Locally indications of weak bedding can be found. The clast composition of the gravel deposits reflects the lithology in the catchment area according to the resistance of the material against glacial abrasion. Only the remnants of basal till on the up-flow side of the terminal moraine are highly consolidated (Fig. 1). The till is normally slightly weathered to depths ranging between 0.5 and maximum 1 m.

Genetically, the Würm-Endmoräne is a terminal moraine which was (predominantly) deposited as a dump moraine by a stationary glacier (Fig. 1). It marks the maximum ice extent during the last pleniglacial conditions in all valleys originating from formerly glaciated regions.

Within these areas a patchy cover of Würm basal till (German: Grundmoräne) i.e. overconsolidated massive matrix-supported diamicton with occasional shear planes) on top of pre-Quaternary bedrock as well as on older Pleistocene sediments is present. The contact is in most cases unconformable. The thickness of the till varies from some meters to 40 m at drumlins. Generally, the basal till can be classified as a subglacial traction till (Evans et al. 2006).

"Würm-Vorstoßsedimente" is a term used for sediments which are coverd by Würm basal till and whose facies indicates deposition in the proglacial area (sensu lato) of glaciers advancing to their maximum extent during the Würm Pleniglacial. This includes sediments of different facies (fluvial, alluvial, glacio-fluvial, lacustrine and glaciolacustrine). Around the terminal moraines such sediments below basal till are typically gravel beds so called "Vorstoßschotter" (Penck & Brückner 1909) of some meters thickness. Within the Alpine valleys up to 100 m thick sediment sequences of such coarse sand-bearing gravel are preserved (van Husen 2000a) (see Figs. 1 & 14). Prominent examples are found in the lower Inn valley (east of Innsbruck, especially around the village of Baumkirchen), the Drau valley near Spittal/Drau (Schotter von St. Peter in Holz; Schuster, Pestal & Reitner 2006) and in the Gail valley (Schönlaub 1989) (all locations in Fig. 4). Only under special circumstances also thick layers of banded clay occur (e.g. Baumkirchen, E of Innsbruck, Figs. 1, 4 & 15, Fliri et al. 1970, Fliri 1973). All these gravel beds as well as fine grained sediments are showing coarsening upwards sequences and mostly a transition into the overlaying Würm basal till. The banded clay of Baumkirchen contains macro plant remains (branches of pine, alder, buckthorn) with ^{14}C ages of 31–27 ka BP and pollen indicating cold climatic conditions with a shrub tundra surrounding the former lake (Fliri 1973). A branch of Alnus from the deposit at Podlanig (Gail valley, Fig. 1) with a ^{14}C age of 28.3 ± 0.7 ka (van Husen 1989) as well documents ice-free conditions and strong aggradation in the big valleys during that time.

The Würm-Moräne is correlated with the Late Würm (Chaline & Jerz, 1984) and thus with MIS 2, whereas the banded clay of Baumkirchen is correlated with the Middle Würm (Chaline & Jerz, 1984) and with MIS 3. The onset of proglacial gravel on top of the banded clay at Baumkirchen marks the beginning of the Late Würm (MIS 2) after Chaline & Jerz (1984).

Niederterrasse

The term meaning low terrace in English was introduced by Penck during geological mapping in the Bavarian Alpine Foreland (eg. Geol. Karte Ingolstadt). The type area was first around Ingolstadt and later in the Iller-Lech-Platte. Originally the name was connected with the lowest of the extensive valley terraces following the modern river course (Fig. 2). Later it was considered to be the meltwater accumulation of the last glacial cycle (Penck & Brückner 1909).

Fig. 14: "Vorstoßschotter" (gravelly facies of "Vorstoßsedimente") representing proglacial sediments overlain by Würm basal till (gravel pit near Baumkirchen). Note the poor sorting and the large boulders in the gravel.

Abb. 14: „Vorstoßschotter" (kiesige Fazies der „Vorstoßsedimente"), ein typisches Sediment aus dem Gletschervorfeld, überlagert von Würm-Grundmoräne (basal till) (Schottergrube bei Baumkirchen). Die schlechte Sortierung und die Größe der Gerölle im Schotter sind auffallend.

Fig. 15: Outcrop at the abandoned clay pit at Baumkirchen with typical banded clay.

Abb. 15: Aufschluss in der aufgelassenen Tongrube von Baumkirchen mit dem typischen Bänderton bzw. Bänderschluff.

The terrace deposits consist of coarse, sand-bearing gravel with weak bedding. Gravel composition displays the lithology of the catchment area of the respective rivers. Along the Danube material from the Alps in the South (e. g. limestone, dolomite, flysch, sandstones) is mixed with the gravel from the tributaries originating in the Bohemian Massif. The gravel is usually not cemented and the weathering horizon on top of the sequence is relatively thin. A cover of loessic sediments occurs only at the rim to adjacentolder terraces due to re-deposition. The thickness of the terrace deposits varies between 20–100 m. The gravel deposits are unconformable underlain by pre-Quaternary bedrock.

The gravel of the Niederterrasse derive from fluviale accumulation by braided rivers and are widerspread in more or less all glaciated and non glaciated valleys. Based on the model of the 'Glaziale Serie' (Fig. 1) the Niederterrasse is directly connected with Würm-Moränen (terminal moraines) in more or less all the valleys in the Eastern Alps which were affected by former glaciers (s. Figs. 4 & 5), as for example: the Salzach glacier (Weinberger 1955) and Traun glacier (Egger 1996; Egger & van Husen 2007). Many extensive remnants occur along the Danube and its southern tributaries as well as in the South along the rivers Mur and Drau and their tributaries (Krenmayr & Schnabel et al. 2006; Schnabel et al. 2003). Due to climate controlled congelifraction the Niederterrasse are also developed in non-glaciated areas.

Evidence for deposition in a non-glaciated area is found at Neurath (Stainzbach / SW of Graz) where a gyttja interbedded in gravel beds providing ^{14}C ages of 19,720 ± 390 ka BP and 21,270 ± 230 ka BP marks the end of sedimentation under periglacial conditions (Draxler & van Husen 1991). Based on the outlined processes the deposits of the Niederterrasse are correlated with MIS 2 and 3 and thus to Middle and Late Würm.

Tullner Feld

The name of the unit is derived from the city of Tulln and the unit was first described by Piffl (1971). The type area lies between Krems in the West and Greifenstein in the East on the ÖK 1:50,000 sheets 38 Krems an der Donau, 39 Tulln, 40 Stockerau (Fig. 6).

Lithologically, the Tullner Feld deposits consist of sand-bearing coarse gravel. The material is predominantly rounded and well-rounded. It was deposited by the river Danube. In particular a high content of crystalline rocks mixed with limestone, dolomite and sandstone is observed at the debouchment of tributaries in the southern part of the distributional area. The gravel deposits are horizontally layered with cross bedding. Wide-spread layers of sand occur particularly north of the Danube. Weathering is restricted to about the uppermost 50 cm. Gravel deposits south of the Danube display permafrost features like cryoturbation and ice wedges. Large and usually angular boulders of 1 m and more in diameter occur frequently at the base of the gravel deposits near the underlying bedrock .

The thickness of the terrace deposits varies between 10–20 m. An unconformity at the base of the gravel deposits marks the transition to the Neogene deposits of the Molasse Basin.

Sedimentological charateristics of braided river type, permafrost structures, and poor weathering in the area south of the Danube point to accumulation of the deposits during glacial conditions (Piffl 1971). On the contrary, the gravel deposits in the area north of the Danube show sediment structures typical for meandering rivers as a result of complete re-working of the glacial terrace by the river Danube. Such process took place without lowering of the surface and basal erosion level compared to that of the glacial terrace in the sense of the Niederterrasse. This re-working without incision by the river Danube resulted from the large debris load supplied from the tributaries while they eroded their local Niederterrassen deposits (van Husen 2000a).

The chronostratigraphic age of the sediments in the Tullner Feld is correlated with the Late Würm (MIS 2) for the area south of the Danube and with the Early Holocene for the area north of the Danube. The latter is supported by ^{14}C dates of about 9–9.7 ka BP which are obtained from tree trunks of oak, elm, poplar, and willow.

Prater Terrasse

The terrace was first discussed by Schaffer (1902), Fink & Majdan (1954), Küpper (1968) and Fink (1973). The type area of the Prater Terrasse (terrace) is the SE part of the island between Danube and Danube canal in the 2nd district of Vienna (Fig. 7; ÖK 1:50,000 sheet 59 Wien). The name is derived from an extensive and well-know recreation area in Vienna characterized by meadows and forest.

The thickness of the gravel deposits amounts some 10 m and the sediments are unconformable underlain by Neogene deposits of the Vienna Basin.

The deposits of the Prater Terrasse consist of coarse gravel and sand with predominantly rounded and well-rounded components transported by the river Danube. A high content of crystalline rocks mixed with limestone, dolomite and sandstone is observed particularly around the mouths of tributaries. In the Marchfeld north of the Danube the gravel shows horizontal layering and cross bedding while intercalated wide-spread layers of sand occur frequently. At some locations north of the Danube permafrost features like cryoturbations and ice wedges were described (Fink & Majdan 1954). The about uppermost 50 cm of the deposits are affected by weathering. At the base and partly also within the gravel deposits near the bedrock large and mostly angular boulders of 1 m and more in diameter occur frequently (Küpper 1950). These were transported and deposited by ice floes under glacial conditions.

According to braided river sediment structures and permafrost features as well as poor weathering the Prater Terrasse in the northern part of the Marchfeld north of the Danube was considered to represent glacial conditions (Fink & Majdan 1954, Küpper 1968, Fink 1973). In contrast the gravel deposits of the Danube south of this area are partly characterized by sediment structures of meandering rivers. The Danube has only reworked the material of the glacial terrace without lowering the elevation of the surface by erosion. This was due to the debris load the Danube had to carry from the tributaries, eroding their Niederterrassen (van Husen 2000a). Thus the northern parts of the Prater Terrasse are correlated with the Late Würm (Chaline & Jerz, 1984) and with MIS 2. Reworked terrace sediments are considered to be Early Holocene. Tree trunks (oak, elm, poplar, willow) especially in the Marchfeld north of the Danube were dated at about 8500–7000 ^{14}C years BP (Fink 1973).

Leibnitzer Feld, Grazer Feld

The names were introduced by Penck & Brückner (1909) as local expressions of the Niederterrasse. Descriptions were published by Winkler-Hermaden (1955) and Fink (1961). The type area is the Mur valley south of the city of Graz (ÖK 1:50,000 sheet 190 Leibnitz). The names are derived from the cities of Graz and Leibnitz (Fig. 4).

The gravel deposits of the river Mur consists of coarse material mixed with sandy and contain boulders. The sediment shows intensive cross bedding. The thickness is about 15 m. The deposits are unconformably underlain by Neogene sediments.

The gravel was deposited by braided rivers presumably during the Late Würm (MIS 2).

Long sections

Mitterndorfer Senke, Steinfeldschotter

The first description was given by Sueß (1862), Stiny (1932), and Küpper (1950). The type area is in the southern part of the Vienna Basin (location see Fig. 6; ÖK 1:50,000 sheets 59 Wien, 60 Bruck a.d. Leitha, 76 Wiener Neustadt, 105 Neunkirchen, 106 Aspang). The name of the Mitterndorf basin is derrived from the village Mitterndorf whereas that of the Steinfeld gravel originates from a field name SW of Wiener Neustadt. The Wöllersdorfer Schotterfläche (Brix 1988) is a synonym.

The Mitterndorf Basin was filled by two alluvial fans, the Piesting River fan in the north [former Wöllersdorfer Schotterfächer] and the Schwarza River Fan [former Neunkirchner Schotterfächer] in the south. Both alluvial fans show a characteristic alluvial fan cyclic sequence development of up to about 2 m thick fine clastic sequences which are alternating with massive, fine to coarse gravel (Salcher & Wagreich 2010). The uppermost coarse gravel unit of the whole sequence is called Steinfeldschotter. The thickness of the whole sequence is up to 170 m consisting of different units with thicknesses reaching up to ~35 m. It unconformably overlays Neogene sediments of the Vienna Basin.

The fine clastic facies assemblage is recognized in the lithology of a drillhole as brown to red brown loam or sandy loam with a varying gravel content. These loamy sequences are laterally extensive and can be correlated between wells across an area larger than 100 km². Such correlations allow the evidence of vertical tectonic movements. Massive, coarse sediments of alluvial fans are sheet flow dominated (bed load sheets). Close to the mountain front they are debris flow dominated. Coarse sediment deposition on the fan surface is supposed to occur during rather cold periods where intenisified periglacial influence leads to an increased sediment supply (Salcher & Wagreich 2010). Analogues from outcrops and a scientific cored drillhole (scientific THER-1) suggest that the loamy sequences represent overbank fines in most cases. Such fine clastic deposits are rich in terrestrial molluscs faunas and point to climatically rather warm periods. (Küpper 1950, Salcher & Wagreich 2010).

Preliminary results from mollusc assemblages of cored overbank fines from the bottom of the basin confirm a Middle to Late Pleistocene age of the sediments in the Mitterndorf Basin (Küpper 1950, Decker, Peresson & Hinsch 2005, Salcher & Wagreich 2010). Based on the characteristics of the sequence and luminescence dating results the infill of this tectonically formed Mitterndorf Basin may have started around MIS 7 (Salcher, personal communication). The youngest coarse gravel unit, the Steinfeldschotter is correlated with the Late Würm and with MIS 2.

Krems Schießstätte

The descriptions were given by Penck (1903), Hoernes (1903), Götzinger (1936) (Kremser Verlehmungszone), and Fink & Piffl (1976 a) for the type area at the eastern slope of Wachtberg North of the city of Krems (location see Fig. 6; ÖK 1:50,000 sheet 38 Krems a.d. Donau). The type section is situated in the local rifle range (German: Schießstätte).

Lithologically it is a 40 m thick loess profile with a sequence of paleosols. Molluscs of warm and cold periods (Ložek 1976) and remnants of tiny mammals (Rabeder 1976) were found. The deposit was formed in a lee position interrupted by weathering horizons (paleosols). According to paleomagnetic investigation (Koci & Kukla 1976) of the section started to develop at the end of the Olduvai event and was continuing through the Brunhes chron (Fink & Kukla 1977).

Stranzendorf

This section was described by Fink & Piffl (1976 b) and Frank & Rabeder (1997 a). The type area is in the southern part of Weinviertel (ÖK 1:50,000 sheet 40 Stockerau). The type section is east of the village of Stranzendorf (location see Fig. 6; N 48°27'10" E 16°05'20").

Lithologically the 40 m thick profile consists of gravel deposited by the Danube with a strong influence of a tributary from the South (Fink & Piffl 1976b, Frank & Rabeder 1997a). The section is overlain by a loess sequence with paleosols (Fink & Piffl 1976, Rabeder & Verginis 1997). A fauna rich in molluscs (Frank & Rabeder 1997a) and vertebrate (Nagel & Rabeder 1991, 1997) was found. According to the fossils the loess sequence was generally deposited under warmer conditions then during the Middle and Late Pleistocene. Changes from cooler and dryer periods (loess sedimentation) to humid and warmer periods with weathering (forest paleosols) occurred frequently (Frank & Rabeder 1997a).

The chronostratigraphic age is correlated with Gelasian and the earliest part of the Early Pleistocene after Frank & Rabeder (1997 a).

Hundsheim-Pfaffenberg-Deutsch Altenberg

Descriptions are given by Toula (1902), Freudenberg (1914), and Ehrenberg (1929). Since 1971 this site hs been intensively investigated by the Institute of Paleontology (University of Vienna). The type area are the Hainburger

Berge around Pfaffenberg (location see Fig. 6; ÖK 1:50,000, sheet 61 Hainburg) with type section in the quarry Hollitzer (Deutsch Altenburg) N 48°08'15", E 16°55'00" and in the Hundsheimer Spalte N 48°08'24", E 16°56'05".

Lithologically the unit consists of cave sediments like talus cemented by sinter, fluvial sand, loess, and transported soil material. A comprehensive and detailed description of the fossils is given by Frank & Rabeder (1997 b, c). The karst caves originating in Triassic carbonates were filled with different sediments due to changing sedimentation conditions over a long timespan. At least 50 spots were described (Frank & Rabeder 1997 b, c).

The chronostratigraphic age is assumed according biostratigraphic data (Frank & Rabeder 1997 b, c) to range from Middle Pliocene to Middle Pleistocene.

Discussion and Conclusions

The stratigraphic framework for the Quaternary of Austria (Fig. 3) summarizes our current knowledge on climatically controlled sedimentation as well as on tectonic processes like uplift or subsidendence. It provides guidelines especially for the classification of terraces of the Alpine foreland which are connected via the Glaziale Serie (Penck & Brückner, 1909) to the glacial sediments of the four well documented glaciations of Middle to Late Pleistocene age. Based on facies, weathering and position along the valleys the stratigraphic positions of separated terrace units can be established. However, such a correlation within the sedimentary inventory of Austria as well as with global archives is very difficult for the isolated and rarely found remnants of Early Pleistocene deposits. The only exception are sediments at Stranzendorf, one of the rare European sites where the Quaternary/Neogene boundary has been pinned down by paleomagnetic evidence. The correlation of lithological units related to the last glaciation (Late Würm) is possible based on well developed facies schemes and on glaciological considerations. However, such an approach has its limitations for sediments below the basal till of the last glaciation. An indisputable stratigraphic correlation of e.g. the "Vorstoßsedimente"/"Vorstoßschotter" is only possible if a continuous sequence including the transition to the basal till is evident like at the type section at Baumkirchen (Chaline & Jerz, 1984) or at similar locations. In the absence of absolute age dates one can never exclude the possibility that an unconformable contact represents a major hiatus and that the sediments above and below are of completely different age. Thus, the examples from both the foreland and the Alpine area illustrate that reliable physical datings by e.g. radiometric methods, luminescence, cosmogenic isotopes or paleomagnetics are strongly needed for deposits older than the last glacial climax and especially for Middle- to Early Pleistocene units to back up stratigraphic correlations.

From the formal stratigraphic point of view the Austrian record of Quaternary sedimentary units resembles a compound stratigraphy including aspects of lithostratigraphy (lithic characteristics) as well as of allostratigraphy (discontinuities/unconformities) for the definition of different units. However, a strict formalization of the terminology as outlined in the North American Stratigraphic Code (NACSN 2005) or by Salvador (1994) only seems to be an exercise in stratigraphy without any added value (compare Piller, van Husen & Schnabel, 2003). Thus at present we do not follow efforts of standardisation which elsewhere result in a plethora of lithostratigraphic subdivisions (e.g., British Isles; Bowen 1999a), which are partly "not amenable to systematic and widespread mapping away from their stratotypes" (Bowen 1999b). A stratigraphy of lithological units which is not applied in geological practise especially in maps is of limited value. In this context it has to be emphasized, that for example the youngest phase of the Quaternary (Würm Lateglacial to Holocene) is documented in geological maps not by stratigraphic units but mostly by lithogenetic unit. In the sense of GeoSciML (Concept Definition Task Group of IUGS CGI Interoperability Working Group 2008, Schiegel et al. 2008) these units such as alluvial fan or ice-marginal deposits are defined by their depositional origin as manifested by material properties. However, there is evidently a need for a critical assessment of the nomenclature especially for units of the Early Pleistocene which are not well described and defined (e.g. Arbesthaler Hügelland, Amstettner Bergland, Rauchenwarter Platte etc.).

In the absence of a regional alternative the MIS stratigraphy serves as a chronostratigraphic frame for correlations with climatic events especially for the Early–Middle Pleistocene. The high resolution record of Greenland ice cores has been applied as a standard for geological time only for some well constrained Late Würm especially Lateglacial sediments (e.g. Boch et al., 2005) and speleothems (e.g., Spötl & Mangini, 2002). The fragmentary sedimentary record in Austria as well as in the northern-alpine foreland, the occurrence of hiatuses and the missing of long records do not promote the development of a regional chronostratigraphy. Long loess sequences like at Stranzendorf and Krems Schießstätte would be candidates for standards, although they also include periods of non-deposition or erosion. The problem of cross-facies correlations and the need for reliable age dates remain within the terrestrial system.

Finally the current knowledge on Quaternary stratigraphy relies on the results of field work covering at most 60 % of the country mapped by modern standards. Hence, further improvements in stratigraphy can be expected from progress in geological mapping as well as from drillholes. New findings, modern re-investigations of type sections and areas as well as better geochronological constraints from modern dating techniques with reference to mapping results, are expected to improve this compound stratigraphy.

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References

Ampferer, O. (1936): Höttinger Breccie und Hafelekar. In: Führer für die Quartär-Exkursionen in Österreich 1. Teil (III. INQUA Konferenz). – Geologische Bundesanstalt, 56–66, Wien.

Angerer, L. (1909): Die Kremsmünsterer Weiße Nagelfluh und der ältere Deckenschotter. – Jahrbuch der k.k. Geologischen Reichsanstalt 59: 23–28, Wien.

Boch, R., Spötl, C., Reitner, J.M. & Kramers, J. (2005): A Lateglacial travertine deposit in Eastern Tyrol (Austria). – Austrian Journal of Earth Sciences, 98: 78–91.

Boué, A. (1830): Mémoires géologiques sur le sol terriaire et alluvial du pied septentrional des Alpes allemandes et dans la Hongrie et la Transylvanie: Part I. Bassins de la Suisse, de la Baviere et de l'Autriche superieure. – Journal de Géologie 2: 333–351, F.G. Levrault, Paris.

Bowen, D. Q. (1978): Quaternary geology: a stratigraphic framework for multidisciplinary work. – 221 p., Pergamon Press, Oxford ; New York

Bowen, D. Q. (1999a): A Revised Correlation of Quaternary Deposits in the British Isles. – Geological Society Special Report, 23: 174 pp. London, Bath.

Bowen, D. Q. (1999b): On the correlation and classification of Quaternary deposits and land-sea correlations.- In: Bowen, D. Q. (ed.): A Revised Correlation of Quaternary Deposits in the British Isles. Geological Society Special Report, 23: 1–9, London, Bath.

Brix, F. & Plöchinger, B. (1982): Geologische Karte der Republik Österreich 1:50,000, Blatt 76 Wiener Neustadt + Erläuterungen (1988). – Geologische Bundesanstalt, Wien.

Chaline, J. & Jerz, H. (1984): Arbeitsergebnisse der Subkommission für Europäische Quartärstratigraphie Stratotypen des Würm-Glazials. – Eiszeitalter und Gegenwart, 35: 185–206, Hannover.

Cohen K.M. & Gibbard, P. (2011): Global chronostratigraphical correlation table for the last 2.7 million years. Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy), Cambridge, England.

Concept Definition Task Group of IUGS CGI Interoperability Working Group (2008): CGI Geologic unit type vocabulary. http://www.cgi-iugs.org/tech_collaboration/interoperability_working_group.html.

Decker, K. Peresson, H. & Hinsch, R. (2005): Active tectonics and Quaternary basin formation along the Vienna Basin Transform fault. – Quaternary Science Reviews 24: 305–320, Amsterdam.

Del Negro, W. (1969): Bemerkungen zu den Kartierungen L. Weinbergers im Traungletschergebiet (Attersee- und Traunseebereich). – Verhandlungen der Geologischen Bundesanstalt: 112–115, Wien

Draxler, I. & Husen van D. (1991): Ein C-14 datiertes Profil in der Niederterrasse bei Neurath. Zeitschrift für Gletscherkunde und Glazialgeologie, 25: 123–130, Innsbruck.

Denk, T. (2006): Rhododendron ponticum L. var. Sebinense (SORDELLI) SORDELLI in the Late Pleistocene flora of Hötting, Northern Calcareous Alps: witness of a climate warmer than today? – Veröffentlichungen des Tiroler Landesmuseums Ferdinandeum, 86, 43–66, Innsbruck.

Drescher-Schneider, R. (2000): Die Vegetations- und Klimaentwicklung im Riß/Würm-Interglazial und im Früh- und Mittelwürm in der Umgebung von Mondsee. Ergebnisse der pollenanalytischen Untersuchungen. In: Klimaentwicklung im Riß/Würm Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12: 39–92, Wien.

Ebner, F. (1983): Erläuterungen zur geologischen Basiskarte 1:50.000 der Naturraum Potentialkarte "Mittleres Murtal". – Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich, 29: 99–131, Wien.

Egger, H. (1996): Geologische Karte der Republik Österreich 1:50.000, Blatt 66 Gmunden + Erläuterungen (1997). – Geologische Bundesanstalt, Wien.

Egger, H., & Husen van, D. (2007): Geologische Karte der Republik Österreich 1:50.000, Blatt 67 Grünau + Erläuterungen. – Geologische Bundesanstalt

Egger, H., & Husen van, D. (2003): Geologische Karte der Republik Österreich 1:50.000, Blatt 64 Straßwalchen. – Geologische Bundesanstalt

Ehrenberg, K. 1929: Zur Frage der systematischen und phyllogenetischen Stellung der Bärenreste von Hundsheim und Deutsch-Altenburg. – Paläobiologica, **2**: 213–221, Wien.

Escher von der Linth, A. (1846): Beiträge zur Kenntnis der Tiroler und Bairischen Alpen. – Neues Jahrbuch für Mineralogie, Geognosie, Geologie und Petrefaktenkunde, 1846: 536–561, Leonhardt und Bronn.

Ettinghausen C. V. (1885): Über die fossile Flora der Höttinger Breccie. – Sitzungsberichte der Akademie der Wissenschaften 90: 1–16, Wien.

Evans, D.J.A., Phillips, E.R. Hiemstra, J.F., Auton, C.A. (2006): Subglacial till: Formation, sedimentary characteristics and classification. – Earth-Science Reviews, 78: 115–176.

Felber, H. & Husen van, D. (1976): Eine Innerwürmeiszeitliche Seeablagerung im Freibachtal (Kärnten). – Zeitschrift für Gletscherkunde und Glazialgeologie, 11: 195–201, Innsbruck.

Fink, J. (1961): Die Südostabdachung der Alpen. – Mitteilungen der österreichischen bodenkundlichen Gesellschaft, 6: 123–183, Wien.

Fink, J. (1973): Zur Morphogenese des Wiener Raumes. – Zeitschrift für Geomorphologie, Neue Folge, Supplementbände, 17: 91–117, Berlin Stuttgart.

Fink, J. & Majdan, H. (1954): Zur Gliederung der pleistozänen Terrassen des Wiener Raums. – Jahrbuch der Geologischen Bundesanstalt, 97: 211–249, Wien.

Fink, J. & Piffl, L. (1976 a): Schießstätte Krems.- In: Fink et al.: Exkursion durch den Österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1: 81–83, Wien.

Fink, J. & Piffl, L.(1976 b): Stranzendorf. – In: Fink et al. (eds.): Exkursion durch den Österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1:101–104, Wien.

Fink, J. & Piffl, L. (1976 c): Gneixendorf-Ziegelwerk W Langenlois (Hammer). – In: Fink et al.: Exkursion durch den Österreichischen Teil des nördlichen Alpenvor-landes und den Donauraum zwischen Krems und Wiener Pforte. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1: 91–94, Wien.

Fink, J. & Kukla, J. (1977): Pleistocene Climates in Central Europe: At least 17 Interglacials After the Olduvai Event – Quaternary Research, 8: 363–371.

Fischer, H. (1979): Reliefgenerationen im Kristallinmassiv Donauraum Alpenvorland und Alpenrand im westl. Niederösterreich. – Forschg. Dt. Landesk., 213, Trier.

Fliri, F. (1973): Beiträge zur Geschichte der alpinen Würmvereisung: Forschungen am Bänderton von Baumkirchen (Inntal, Nordtirol). – Zeitschrift für Geomorphologie, Neue Folge, Supplementbände, 16, 1–14, Stuttgart.

Fliri, F., Bortenschlager, S., Felber, H., Heissel, W., Hilscher, H. & Resch, W. (1970): Die Bändertone von Baumkirchen (Inntal, Tirol). – Eine Schlüssselstelle zur Kenntnis der Würmvereisung der Alpen. – Zeitschrift für Gletscherkunde und Glazialgeologie, 6: 5–35, Innsbruck.

Frank, C. & Rabeder, G. (1997a): Stranzendorf. – In: Döppes, D. & Rabeder, G. (eds.) Pliozäne und Plesitozäne Faunen Österreichs. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 130–139, Wien.

Frank, C. & Rabeder, G. (1997b): Deutsch-Altenburg.- In: Döppes, D. & Rabeder, G. (eds.) Pliozäne und Plesitozäne Faunen Österreichs. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 270–274, Wien.

Frank, C. & Rabeder, G. (1997c): Hundsheim. – In: Döppes, D. & Rabeder, G (eds.) Pliozäne und Plesitozäne Faunen Österreichs. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 238–270, Wien

Frank, C. & Rabeder, G. (1997d): Neudegg. – In: Döppes, D. & Rabeder, G. (eds.) Pliozäne und Plesitozäne Faunen Österreichs. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 10: 106–110, Wien.

Freudenberg, W. (1914): Die Säugetiere des älteren Quartärs von Mitteleuropa, mit bes. Berücksichtigung der Fauna von Hundsheim und Deutsch-Altenburg in Niederösterreich. – Geologisch-Paläontologische Abhandlungen Neue Folge, 12: 455–671, Jena.

Fritz, A. (1992): Fagus-reiche Waldbestände im Riss/Würm – Interglazial des südöstlichen Alpenraumes. – Carinthia II 102: 597–610, Klagenfurt.

Fuchs, W. (1964): Tertiär und Quartär in der Umgebung von Melk. – Verhandlungen der Geologischen Bundesanstalt 1964: 283–299, Wien.

Fuchs, W. (1985a): Geologische Karte der Republik Österreich 1:50.000, Blatt79 Neusiedl am See – 80 Ungarisch Altenburg – 109 Pamhagen. – Geologische Bundesanstalt, Wien.

Fuchs, W. (1985b): Geologische Karte der Republik Österreich 1:50.000, Blatt 61 Hainburg a.d. Donau – 62 Pressburg. – Geologische Bundesanstalt, Wien.

Fuchs, W. (1985c): Geologische Karte der Republik Österreich 1:50.000, Blatt 60 Bruck a.d. Leitha. – Geologische Bundesanstalt, Wien.
Fuchs, W. (1985d): Geologische Karte der Republik Österreich 1:50.000, Blatt 59 Wien. – Geologische Bundesanstalt, Wien.
Fuchs, W. & Grill, R. (1984): Geologische Karte von Wien und Umgebung 1:200.000. – Geologische Bundesanstalt, Wien.
Gams, H. (1936): Die Flora der Höttinger Breccie. In: Führer für die Quartär-Exkursionen in Österreich 1. Teil (III. INQUA Konferenz). – Geologische Bundesanstalt, 67–72, Wien.
Gemmell, A.M.D. & Spötl, C. (2009): Dating the Hötting Breccia near Innsbruck (Austria), a classical Quaternary site in the Alps. – Austrian Journal of Earth Sciences, 102: 50–61.
Geyh, M.A., Hennig, G. & Oezen, D. (1997): U/Th-Datierung interglazialer und interstadialer Niedermoortorfe und Lignite – Stand und Zukunft. Schriftenreihe der Deutschen Geologischen Gesellschaft, 4: 187–199, Hannover.
Gibbard, P.L. (2003): Definition of the Middle-Upper Pleistocene boundary. – Global and Planetary Change 36: 201–208.
Gibbard, P. Head, M.J., Walker, M.J.C. & The Subcommission on Quaternary Stratigraphy (2010): Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. – Journal of Quaternary Science, 25: 96–102.
Gibbard, P. & Cohen, K.M. (2008): Global chronostratigraphical correlation table for the last 2.7 million years. – Episodes, 31: 243–247.
Gibbard, P. L. & West, R. G. (2000): Quaternary chronostratigraphy: the nomenclature of terrestrial sequences. – Boreas, 29: 329–336, Oslo.
Götzinger, G. (1936): Salzburg und der Gaisberg. In: Führer für die Quartär-Exkursionen in Österreich 1. Teil (III. INQUA Konferenz). – Geologische Bundesanstalt, 135–148, Wien.
Götzinger, G. (1936): Das Lößgebiet um Göttweig und Krems a.d. Donau. In: Führer für die Quartär-Exkursionen in Österreich 1. Teil (III. INQUA Konferenz). – Geologische Bundesanstalt, 135–148, Wien.
Grill, R. (1951): Exkursion in das Korneuburger und das nördliche inneralpine Wiener Becken. – Verhandlungen der Geologischen Bundesanstalt, Sonderheft A: 1–20, Wien.
Grüger, E. (1979): Spätriss, Riss/Würm und Frühwürm am Samerberg in Oberbayern – ein vegetationsgeschichtlicher Beitrag zur Gliederung des Jungpleistozäns. – Geol. Bavarica 80: 5–64, Munich.
Häusler, H. (2007): Erläuterungen zu den Blättern 79 Neusiedl am See – 80 Ungarisch Altenburg – 109 Pamhagen. – 88 p., Geologische Bundesanstalt, Wien.
Head, M.J & Gibbard, P.L. (2005): Early-Middle Pleistocene transitions: an overview and recommendation for the defining boundary. In: Head, M.J. & Gibbard, P.L. (eds.) 2005. Early-Middle Pleistocene transitions: the land-ocean evidence. Geological Society of London, Special Publication, 247:1–18.
Hoernes, R. (1903): Bau und Bild der Ebenen Österreichs. – Tempsky, Wien.
Kieslinger, A. (1964): Die nutzbaren Gesteine Salzburgs. – 436 p., Bergland Buch, Salzburg.
Klebelsberg, R.v. (1948): Handbuch der Gletscherkunde und Glazialgeologie. – 1028 p., Springer, Wien.
Koci, A. & Kukla, J. (1976): Paläomagnetische Untersuchungen. In: Fink et al.: Exkursion durch den Österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1: 88–90, Wien.
Kohl, H. (1977): Kremsmünster, eine Schlüsselstelle für die Eiszeitforschung im Nördlichen Alpenvorland. – 120. Jahresbericht des Stiftsgymnasiums Kremsmünster: 245–254.
Kohl, H., (2000): Das Eiszeitalter in Oberösterreich. – Schriftenreihe des Oberösterreichischen Musealvereins, 17, 487 p, Linz.
Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., Schlüchter, C. (2009): Latest Pleistocene and Holocene glacier variations in the European Alps. – Quaternary Science Reviews, 28: 2137–2149.
Krenmayr, H.G. (1996): Geologische Karte der Republik Österreich 1:50.000, Blatt 49 Wels + Erläuterungen (1997). – Geologische Bundesanstalt, Wien.
Krenmayr, H.G. (2000): Sedimentologie der letzt-interglazialen bis Mittelwürm-zeitlichen Seesedimente bei Mondsee. In: Klimaentwicklung im Riß/Würm Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6–3) in den Ostalpen. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12: 13–37, Wien.
Krenmayr, H.G & Schnabel, W. 2006: Geologische Karte von Oberösterreich 1:200.000. – Geologische Bundesanstalt, Wien.
Küpper, H. (1950a): Eiszeitspuren im Gebiet von Wien. – Sitzungsberichte / Österreichische Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse, 159, 199–206, Wien.
Küpper, H. (1950b): Zur Kenntnis des Alpenabbruches am Westrand des Wiener Beckens. – Jahrbuch der Geologischen Bundesanstalt, 94: 41–92, Wien.
Küpper, H. (1968): Wien. Geologie der Österreichischen Bundesländer. – Verhandlungen der Geologischen Bundesanstalt, Bundesländerserie Heft Wien.
Ložek, V. (1976): Malakologie. In: Fink et al.(eds.): Exkursion durch den Österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1, 84–87, Wien.
Megies, H. (2006): Kartierung, Datierung und umweltgeschichtliche Bedeutung der jungquartären Flussterrassen am unteren Inn. – Heidelberger Geographische Arbeiten, 120, 207 p., Heidelberg.
Morlot, A.v. (1847): Erläuterungen zur geologischen Übersichtskarte der nordöstlichen Alpen. Ein Entwurf zur vorzunehmenden Bearbeitung der physikalischen Geographie und Geologie ihres Gebietes. – 212 p., Wien (Braumüller & Seidel).
Muttoni G., Carcano, C., Garzanti E., Ghielmi M., Piccin, A., Pini, R., Rogledi S., and Sciunnach D. (2003): Onset of major Pleistocene glaciations in the Alps. – Geology, 31: 989–992.
Muttoni G., Ravazzi C., Breda M., Laj C., Kissel C., Mazaud A., Pini R., Garzanti E (2007): Magnetostratigraphy of the Leffe lacustrine succession (Southern Alps, Italy): evidence for an intensification of glacial activity in the Alps at Marine Isotope Stage 22 (0.87 Ma). – Quaternary Research, 67: 161–173.
Nagl, D. & Rabeder, G. (1991): Exkursionen im Pliozän und Pleistozän Österreichs. – Österreichische Paläontologische Gesellschaft, 44 p. Wien
North American Commission on Stratigraphic Nomenclature (NACSN), (2005): North American Stratigraphic Code. – American Association of Petroleum Geologists Bulletin 89: 1547–1591.
Oeggl, K. & Unterfrauner, H. (2000): Die Pflanzenreste des Riß/Würm Interglazials und des Würmglazials von Mondsee. In: Klimaentwicklung im Riß/Würm Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12: 93–121, Wien.
Ohnesorge, T. (1917): Geologische Karte von Kitzbühel und Umgebung 1:25.000, Geologische Bundesanstalt, Wien.
Penck, A. 1903: Führer für die Exkursionen des 9. Internationalen Geologen Kongreß in Wien. Exkursionen in das Durchbruchtal der Wachau und die Lößlandschaft von Krems. – IX. Internationaler Geologen-Kongreß, Führer für die Exkursionen, 19 p., Brüder Hollinek, Wien.
Penck, A. (1921): Die Höttinger Breccie und die Inntalterrasse nördlich Innsbruck. – Abhandlungen der Preußischen Akademie der Wissenschaften, 135 p., Berlin.
Penck, A. & Brückner, E.(1909): Die Alpen im Eiszeitalter. – 1199 p., Tauchnitz, Leipzig.
Piffl, L. (1959): Die altpleistozänen Schotterfluren um Langenlois. – Verhandlungen der Geologischen Bundesanstalt, 1959: 132–140, Wien.
Piffl, L. (1971): Zur Gliederung des Tullner Feldes. – Annalen des Naturhistorischen Museums Wien, 75: 293–310, Wien
Piller, W. E., Husen van, D.& Schnabel, W. (2003): Zur Lithostratigraphischen Handhabung quartärer Sedimente und deren Darstellung auf geologischen Karten. Stratigraphia Austriaca. – Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, 16: 7–10, Wien.
Pippan, T.(1957): Bericht 1956 über geologische Aufnahmen auf den Blättern Hallein (94/1) und Untersberg (93/1 1:25.000). – Verhandlungen der Geologischen Bundesanstalt, 1957, 52–56, Wien.
Rabeder, G. (1976): Kleinsäugerreste. In: Fink et al. (eds.): Exkursion durch den Österreichischen Teil des nördlichen Alpenvorlandes und den Donauraum zwischen Krems und Wiener Pforte. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 1: 87–88, Wien.
Rabeder, G. & Verginis, S. (1987): Die plio-pleistozänen Lößprofile von Stranzendorf und Krems (Niederösterreich) – Griechische Geographische Gesellschaft, 1. Panhellenische Geographen-Tagung, Athen, 9: 285–306, Athen.
Raymo, M.E. (1997): The Timing of Major Climatic Terminations. – Paleooceanography 12: 577–585.
Reitner, J.M. (2005): Quartärgeologie und Landschaftsentwicklung im Raum Kitzbühel – St. Johann i.T. – Hopfgarten (Nordtirol) vom Riss

bis in das Würm-Spätglazial (MIS 6-2). Dissertation, 190 p., Universität Wien.

Reitner, J.M. (2007): Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications. – Quaternary International, 164–165: 64–84.

Reitner, J. & Draxler, I. (2002): Die klimatisch-fazielle Entwicklung vor dem Würm -Maximum im Raum Kitzbühel – St. Johann-Hopfgarten (Nordtirol/Österreich). – Terra Nostra 2002/6: 298–308, Potsdam.

Richmond, G. M. (1996): The INQUA-approved provisional Lower-Middle Pleistocene boundary. In: Turner, C. (ed.) The Early-Middle Pleistocene in Europe: 319–326, Balkema, Rotterdam.

Rupp, C. (2008): Geologische Karte der Republik Österreich 1:50.000, Blatt 47 Ried im Innkreis + Erläuterungen. – Geologische Bundesanstalt, Wien.

Schönlaub, H.P. (1989): Geologische Karte der Republik Österreich 1:50.000, Blatt 199 Hermagor – Geologische Bundesanstalt, Wien.

Salcher, B.C., Wagreich, M. (2010): Climate and tectonic controls on Pleistocene sequence development and river evolution in the Southern Vienna Basin (Austria). – Quaternary International, 222, 154–167.

Salvador, A. (1994): International Stratigraphic Guide. – 214 p. International Union of Geological Sciences and Geological Society of America.

Sanders, D. & Ostermann, M. (2006): Depositional setting of the sedimentary rocks containing the "warm-interglacial" fossil flora of the Höttinger Brekzie (Pleistocene, Northern Calcareous Alps, Austria): a reconstruction. – Veröff. Tirol. Landesm. Ferdinandeum, 86, 91–118, Innsbruck.

Sanders, D., Ostermann, M. & Kramers, J. (2009): Quaternary carbonate-rocky talus slope successions (Eastern Alps, Austria): sedimentary facies and facies architecture. – Facies, 55: 345–373.

Schaffer, F. X. 1902: Die alten Flussterrassen im Gemeindegebiet der Stadt Wien. – Geogr. Ges. Wien, 11/12, 325–331, Wien.

Schiegl, M., Schuster, R., Krenmayr, H.-G., Lipiarski, P., Pestal, G., Stöckl, W., Untersweg, T. 2008: GeoSciML – Ein konzeptionelles Datenmodell für die Geologie? Übersetzung und Erläuterung ausgewählter Objektklassen von GeoSciML. – Jahrbuch der Geologischen Bundesanstalt 148: 213–226.

Schnabel, W. (2002): Geologische Karte von Niederösterreich + Erläuterungen. – Geologische Bundesanstalt, Wien.

Schuster, R., Pestal, G. & Reitner, J. M. (2006): Erläuterungen zu Blatt 182, Spittal an der Drau. – 115 p., Geologische Bundesanstalt, Wien.

Spötl, C. & Mangini, A. (2002): Stalagmite from the Austrian Alps reveals Dansgaard-Oeschger events during isotope stage 3: Implications for the absolute chronology of Greenland ice cores. – Earth and Planetary Science Letters, 203: 507–518.

Sueß, E. (1862): Der Boden der Stadt Wien. – 326 p. Braumüller, Wien.

Stiny, J. (1932): Zur Kenntnis jugendlicher Krustenbewegungen im Wiener Becken. – Jahrbuch der Geologischen Bundesanstalt, 82: 75–102, Wien.

Terhorst, B., Frechen, M. & Reitner, J. (2002): Chronostratigraphische Ergebnisse aus Lößprofilen der Inn- und Traun-Hochterrassen in Oberösterreich. – Zeitschrift für Geomorphologie, Neue Folge, Supplementbände, 127: 213–232, Berlin – Stuttgart.

Toula, F. (1902): Das Nashorn von Hundsheim, Rhinoceros (Ceratorhinos) hundsheimensis nov. form. – Abhandlungen der k.k. Geologischen Reichsanstalt, 13, Wien.

Unger, F. (1836): Ueber den Einfluß des Bodens auf die Vertheilung der Gewächse, nachgewiesen in der Vegetation des nordöstlichen Tirols, 368 p., Rohrmann & Schweigerd, Wien.

van Husen, D.(1989): Geologische Karte der Republik Österreich 1:50.000, Blatt 65 Mondsee. – Geologische Bundesanstalt.

van Husen, D. (1977): Zur Fazies und Stratigraphie der jungpleistozänen Ablagerungen im Trauntal. – Jahrbuch der Geologische Bundesanstalt, 120: 1–130, Wien.

van Husen, D. (1997): LGM and Late Glacial Fluctuations in the Eastern Alps. – Quaternary International, 38: 109–118.

van Husen, D. (2000a): Geological Processes during the Quaternary. – Mitteilungen der Österreichischen Geologischen Gesellschaft, 92: 135–156, Wien.

van Husen, D. (ed.) (2000b) :Klimaentwicklung im Riß/Würm Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12, 180 p., Wien.

van Husen, D. (2000c): Die paläogeographische Situation des Mondsees im Riß/Würm Interglazial und Frühwürm. In: Klimaentwicklung im Riß/Würm Interglazial (Eem) und Frühwürm (Sauerstoffisotopenstufe 6-3) in den Ostalpen. – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 12: 9–12, Wien.

van Husen, D. & Reitner J. M. (2011): Klimagesteuerte Terrassen- und Lössbildung auf der Traun-Enns-Platte und ihre zeitliche Stellung (Das Profil Wels/Aschet). – Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften, 19: 1–11, Wien.

Weinberger, L. (1955): Exkursion durch das Österreichische Salzachgletschergebiet und die Moränengürtel der Irrsee- und Attersee-Zweige des Traungletschers. – Verhandlungen der Geologischen Bundesanstalt, 1955: 7–34, Wien.

Wessely, G. (1961): Geologie der Hainburger Berge. – Jahrbuch der Geologischen Bundesanstalt, 104: 273–349, Wien.

Wessely, G. (2006): Niederösterreich. Geologie der Österreichischen Bundesländer. – 416 p., Geologische Bundesanstalt, Wien.

Wettstein, R.v. (1892): Die fossile Flora der Höttinger Breccie. – Denkschrift der Akademie der Wissenschaften, 97: 37–50, Wien.

Winkler-Hermaden, A. (1955): Ergebnisse und Probleme der quartären Entwicklungsgeschichte am östlichen Alpensaum außerhalb der Vereisungsgebiete. – Denkschrift der Österreichischen Akademie der Wissenschaften, 110, 180 p., Wien.

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Zagwijn, W.H. (1996): The Cromerian Complex Stage of the Netherlands and correlation with other areas in Europe. – In: Turner, C. (ed.): The Middle Pleistocene in Europe: 145–172; Rotterdam (Balkema).
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