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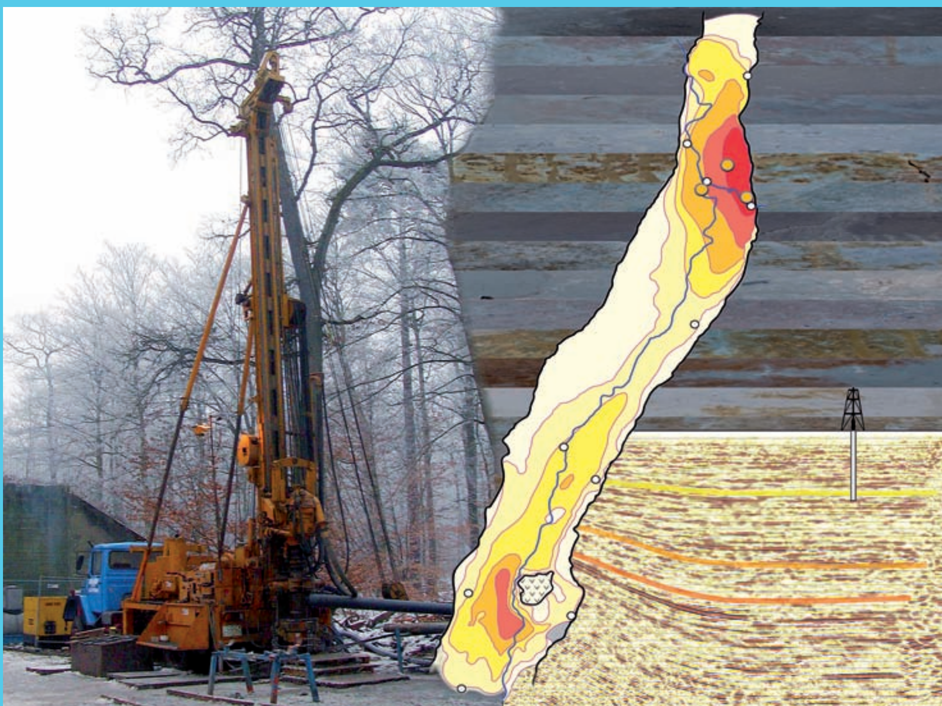

Special issue:

The Heidelberg Basin Drilling Project

Guest editors: Gerald Gabriel, Dietrich Ellwanger, Christian Hoselmann and Michael Weidenfeller

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Titelbild: Collage „Bohrprojekt Heidelberger Becken" (Gestaltung: Juliane Herrmann, Leibniz-Institut für Angewandte Geophysik) Bohranlage an der Lokation Viernheim (Foto: Christian Hoselmann, Hessisches Landesamt für Umwelt und Geologie) – Mächtigkeitskarte der quartären Sedimente im Oberrheingraben (Hessisches Landesamt für Umwelt und Geologie) – reflexionsseismisches Profil in der Umgebung der Forschungsbohrungen Heidelberg UniNord (Hermann Buness, Leibniz-Institut für Angewandte Geophysik) – Bohrkerndetails (Fotos: Christian Hoselmann, Hessisches Landesamt für Umwelt und Geologie)

Front cover: collage „Heidelberg Basin Drilling Project" (design: Juliane Herrmann, Leibniz Institute for Applied Geophysics) drilling rig at the Viernheim location (photo: Christian Hoselmann, Geological Survey of Hessen) – thickness map of Quaternary sediments in the Upper Rhine Graben (Geological Survey of Hessen) – reflection seismic profile in the vicinity of the research boreholes Heidelberg UniNord (Hermann Buness, Leibniz Institute for Applied Geophysics) – core details (photos: Christian Hoselmann, Geological Survey of Hessen)

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Preface: The Heidelberg Basin Drilling Project

Gerald Gabriel, Dietrich Ellwanger, Christian Hoselmann & Michael Weidenfeller

Since Late Pliocene / Early Pleistocene, the River Rhine, as one of the largest European rivers, has acted as the only drainage system that connected the Alps with Northern Europe, especially the North Sea. Along its course from the Alps to the English Channel the river passes several geomorphological and geological units, of which the Upper Rhine Graben acts as the major sediment trap (Fig. 1). Whereas the potential of sediment preservation of the alpine foreland basins is low due to the high dynamics of the system, and the area of deposition close to the North Sea was significantly affected several times by Pleistocene sea level changes, the ongoing subsidence of the Upper Rhine Graben offers a unique potential for a continuous sediment accumulation and preservation. The two major sediment traps are the Geiswasser Basin to the south and the Heidelberg Basin farther to the north. Generally the mean grain size of the deposited alpine sediments in the Upper Rhine Graben decreases from south to north. In the Upper Rhine Graben, the Heidelberg Basin acts as the distal sediment trap for alpine sediments transported northwards by the River Rhine. Here, continuous sediment deposition is less disturbed by significant unconformities than in the south. Therefore, the Heidelberg Basin defines a key location to understand the glacial evolution of the Alps since Late Pliocene, and moreover to compare it with that of Northern Europe (Ellwanger et al. 2005).

The Heidelberg Basin hosts one of the thickest successions of Plio-/Pleistocene sediments in continental Mid-Europe. The Radium Sol Therme borecore drilled during 1913-1918, is located in the centre of the city of Heidelberg, close to the River Neckar. It is controversially discussed in literature. „Base Quaternary“ was interpreted to be at depths of 382 m (Bartz 1951), 400 m (Salomon 1927), or even 650 m (Fezer 1997). Nowadays, from extensive reflection seismics, it is well known that Quaternary deposits are thicker than 300 m. Nevertheless, because reflection seismic surveys were only conducted in the vicinity of Heidelberg but not within the city itself, no detailed information about Quaternary structures has been available for this specific area up to now.

Aiming to better understand the geological evolution of the Heidelberg Basin, its control by climate changes and tectonics, and the correlation of alpine and north European glacial evolution, the Heidelberg Basin Drilling Project was promoted by the Leibniz Institute for Applied Geophysics (LIAG – formerly Leibniz Institute for Applied Geosciences, GGA-Institute) and the three Geological Surveys of Baden-Württemberg, Hessen, and Rheinland-Pfalz. The project focuses on the evolution of the basin since Late Pliocene. Investigations are mainly based on newly cored boreholes at three different locations within the Heidelberg Basin, which represent different types of the basin facies (Fig. 2). Two 300 m deep, cored boreholes in the city of Ludwigshafen – finished in 2002 and 2006 – represent the western margin of the basin. These boreholes were carried out within the framework of groundwater exploration and then left to the Geological Survey of Rheinland-Pfalz. The 350 m deep, cored borehole close to the village of Viernheim should reveal information about the central basin facies. This borehole was carried out and sponsored by the Geological Survey of Hessen and finished in summer 2006. The last of the cored boreholes, the borehole Heidelberg UniNord, is located above the depocentre of the basin, on the eastern margin of the Rhine Graben. This borehole reached its final depth of 500 m in July 2008 and obtained financial support from the Leibniz Institute for Ap-

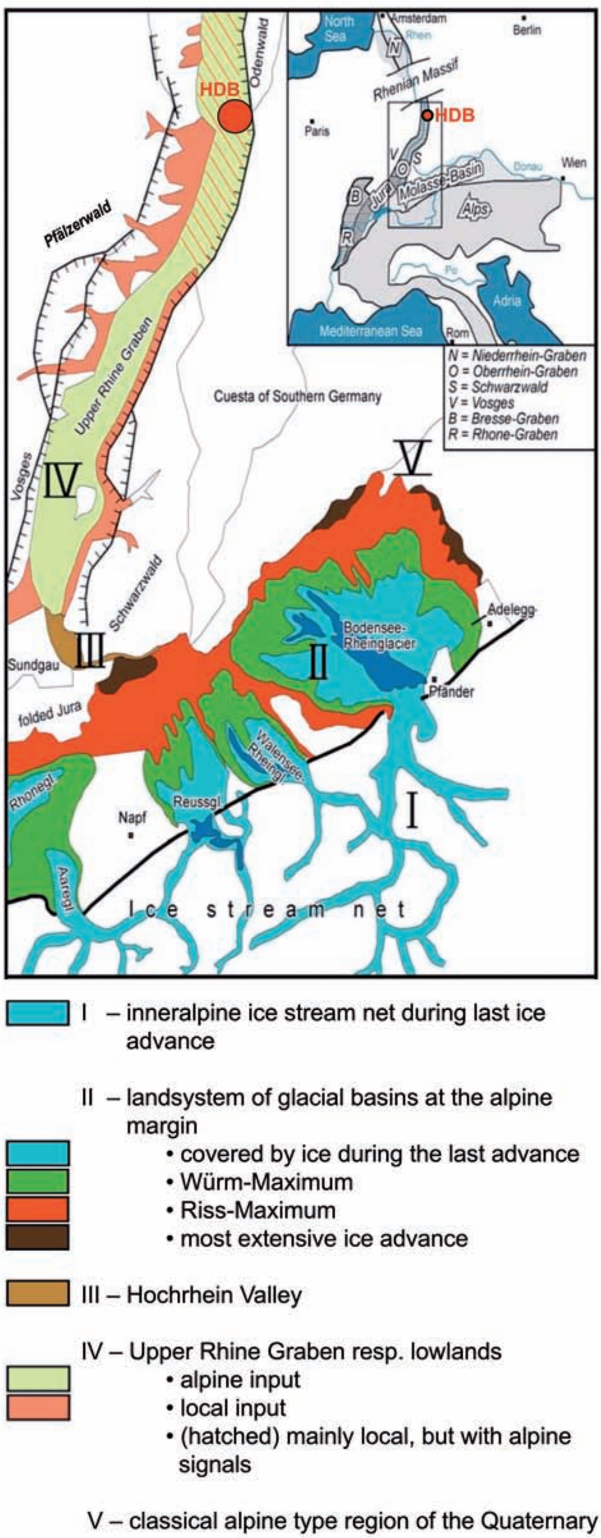

Fig. 1: The Heidelberg Basin (HDB) within the Geosystem „Rhine" (modified after ELLWANGER et al. 2003, 2005).

- Small map: The Upper Rhine Graben as main sediment trap of the Rhine between the Alps and the North Sea.
- Large map: Various landsystems along the Rhine from the Alps to the Upper Rhine Graben.

I – Inneralpine (overdeepened) valleys and the ice stream net of the last ice advance.

II – The landsystem of glacial basins and lakes at the alpine margin, including various ice margins and the ice cover of the last ice advance.

III – Hochrhein valley, terraces and buried valleys.

IV – Upper Rhine Graben and the Upper Rhine lowlands, in the southern part mainly sediments of alpine provenance, in the northern part (hatched) mainly sediments of local provenance (Black Forest, Vosges).

V – The classical pre-alpine meltwater landsystem, type region of the classical glacial units of the Würmian, the Rißian, the Mindelian and the Günzian.

Tab. 1: Lithostratigraphic units as introduced by the three Geological Surveys working on the Heidelberg Basin.

<table>
<tr><th colspan="2">Baden-Württemberg
Symbolschlüssel Geologie Baden-Württemberg</th><th>Rheinland-Pfalz
Weidenfeller & Kärcher 2008
Weidenfeller & Knipping 2008</th><th>Hessen</th><th rowspan="2">Bartz 1982</th></tr>
<tr><td colspan="2"></td><td></td><td>Aeolian sand (Pleistocene to Holocene)</td></tr>
<tr><td colspan="2">Mannheim-Formation</td><td>Upper gravel layer (OKL)</td><td>Sand-gravel layers
Neckar dominated, less alpine</td><td>Oberes Kieslager (OKL)
contains coarse material (alpine and local)</td></tr>
<tr><td rowspan="5">Kurpfalz-Formation</td><td>Ladenburg Horizon</td><td>Upper interlayer (OZH)</td><td>Interlayer
predominant fine-clastic sediments</td><td>Obere Zwischenschicht (OZ)
only fine material</td></tr>
<tr><td rowspan="4">Weinheim Beds</td><td>Middle sand-gravel layer</td><td rowspan="4">Alternation of
sand-(gravel) layers frequently in "Rhenish Facies" and
fine-clastic interlayers
Rhine (alpine) material, less Neckar</td><td>Mittleres Kieslager (MKL)
contains coarse material</td></tr>
<tr><td>Lower interlayer (UZH)</td><td>Untere Zwischenschicht (UZ)
only fine material</td></tr>
<tr><td rowspan="2">Lower sand-silt layer</td><td>Unteres Kieslager (UKL)
contains coarse material</td></tr>
<tr><td>Altquartär 1 and 2 (AQ1 and AQ2)*
transition unit, contains the lowermost alpine material</td></tr>
<tr><td colspan="5">major change of provenance</td></tr>
<tr><td colspan="2">Iffezheim-Formation</td><td>Clay-silt-sand-layer</td><td>Clay-silt- and sand-layers
material of local provenance</td><td>Pliocene I-III *
material of local provenance</td></tr>
</table>

* rather an indication of a sediment type than a strong geochronological classification

plied Geophysics and the Geological Survey of Baden-Württemberg. Combining all new cored boreholes, 1450 m of core material is available now for a detailed investigation program.

At present, no uniform classification for the Plio-/Pleistocene deposits is available for the three federal states, that are working on the Heidelberg Basin, namely Baden-Württemberg, Hessen, and Rheinland-Pfalz. Within each Geological Survey some mandatory guidelines exist that match the specific requirements derived from the local geology. The geology of the southern Upper Rhine Graben on the territory of Baden-Württemberg is significantly affected by the deposition of coarse-grained sediments eroded in the Alps. Therefore, a classification was introduced that considers major unconformities and therefore the dynamic of the sedimentary system in the southern Upper Rhine Graben (Symbolschlüssel Geologie Baden-Württemberg 2007). In contrast, the terminology used in Hessen and Rheinland-Pfalz is built on the systems introduced by Bartz (1982) and HGK (1999), which distinguish between hydrogeological units. At this early stage of the Heidelberg Basin project, it is impossible to set up a uniform nomenclature. Table 1 summarizes the different classifications used in this special issue.

To overcome these discrepancies, investigations in the Heidelberg Basin project must preliminary focus on the establishment of a reference profile of the region north of the Alps, including petrographic, sequence stratigraphic, biostratigraphic, and magnetostratigraphic approaches, complemented by geochronological and geophysical data. Beyond these local to regional aspects, these boreholes offer a sediment archive of supra-regional relevance, particularly regarding the correlation between the glacial evolution in the alpine region and that of Northern Europe. In this context, proxies of past environmental / climate change will be also derived. These aims can only be achieved because the drilled cores reveal a high temporal resolution without significant disconformities

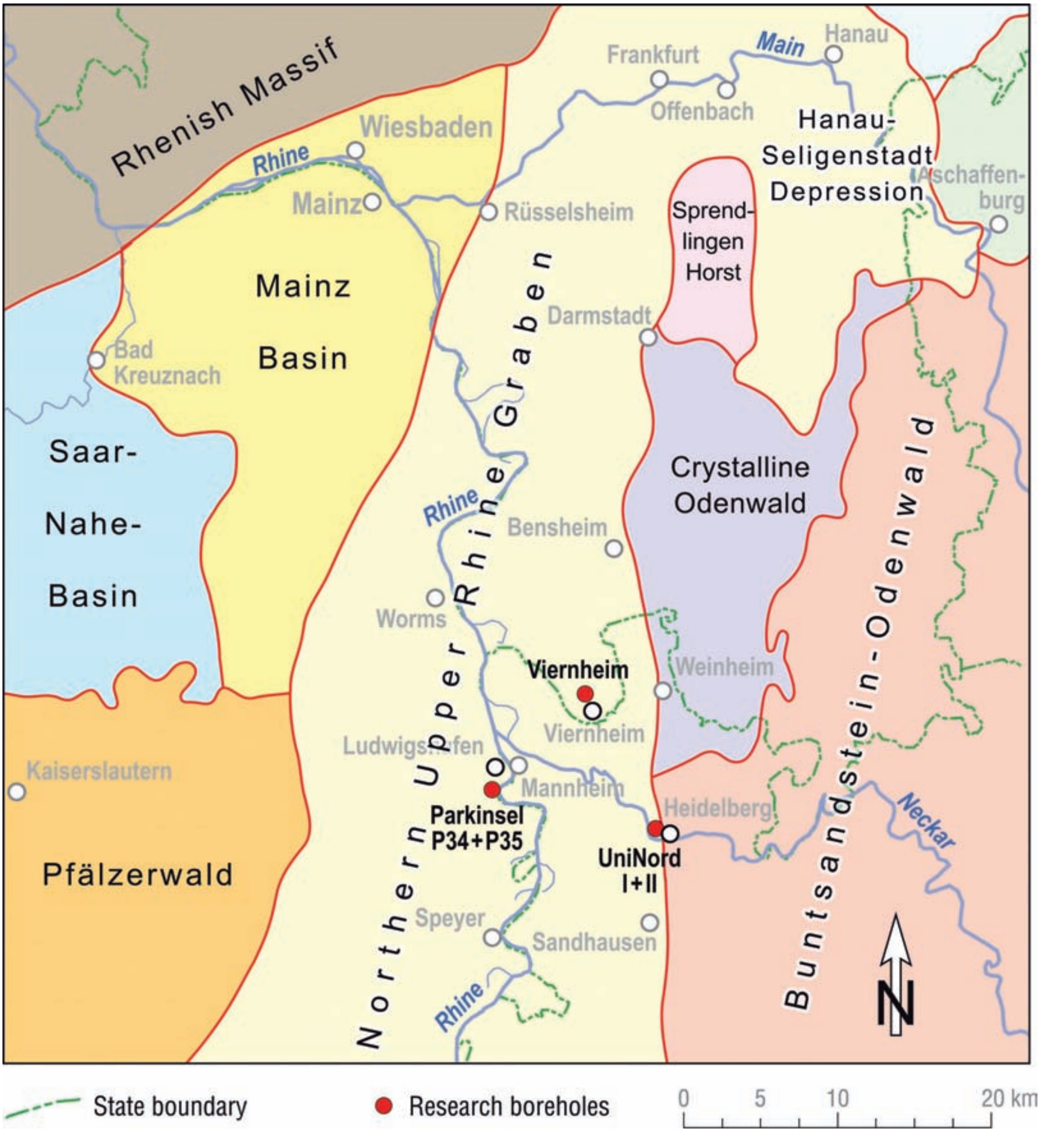

Fig. 2: Geological structural zones with the three borehole locations Ludwigshafen-Parkinsel (cored boreholes P34 and P35, both 300 m deep), Viernheim (350 m deep), and Heidelberg UniNord (research boreholes Heidelberg UniNord 1, 190 m deep, and Heidelberg UniNord 2, 500 m deep) in the Heidelberg Basin.

(Hoselmann et al. 2008). The papers compiled in this special volume of the Quaternary Science Journal (Eiszeitalter und Gegenwart) prove that the drilled cores can be considered as nearly ideal with respect to these aspects.

Due to the availability of the two boreholes in Ludwigshafen at an early stage in this joint project, a comprehensive dataset already exists for this location. Weidenfeller & Knipping (2008) present complementary and consistent datasets as heavy mineral analysis, pollen assemblages and the core description itself. Somewhat surprising the results of the two Ludwigshafen-Parkinsel boreholes differ in some aspects significantly, although the locations lie only 500 m apart. Whereas the upper sections of both boreholes correlate well, thicknesses of individual layers in the deeper part are quite variable. Even the transition between Pliocene and Pleistocene deposits was found at different depths. Consequently this region seems to be affected by tectonics during Upper Pliocene/Lower Pleistocene. These results emphasize that the interpretation of the climatic and fluvial history of an area on the basis of the analysis of only a few boreholes becomes very difficult, not only because the sediments were affected by fluvial dynamics, but also by small-scale tectonics. The distinct characterisation and stratigraphic identification based on several independent methods, and on pollen analysis in particular, are basic requirements for a reliable interpretation of the sedimentation history controlled both by climate and tectonics.

Considering the data available so far, a pattern similar to that in Ludwigshafen is found in the Viernheim borehole (Hoselmann 2008). Based on heavy mineral data, carbonate content, and petrography, the transition Plio/Pleistocene is seen at 225 m depth. However, this boundary is not sharp, but imaged as a transition zone consisting of a reworked horizon. The Pleistocene sediment succession is dominated by alpine sediments, local deposits from the Neckar occur only occasionally. The main part of the Pleistocene section is made up of ten repeated suites that begin with gravely sand layers and end with silty clay sediments or peat. Due to missing pollen data, a detailed correlation with the Ludwigshafen boreholes has not been possible so far. However, Hoselmann (2008) presents a first correlation with other boreholes of the Viernheim-Bensheim region, based on reference markers, e.g. the occurrence of the „Rhenish Facies". Although a general trend of increasing thickness of the Rhenish Facies towards the centre of the Heidelberg Basin in the south is depicted, the fundamental problem of hampered correlation due to the absence of particular beds at some borehole locations is also addressed.

The last of the boreholes to finish was the Heidelberg UniNord at the end of July 2008 (Ellwanger et al. 2008). Based on the information from the reflection seismic surveys and the old Radium Sol Therme borehole, this location was expected to represent the depocentre of the Heidelberg Basin. With respect to the first palynological data, this assumption seems to be confirmed. Even at 420 m depth Quaternary pollen assemblages are found. If this can be confirmed by more detailed studies in future at this location, the thickness of Pleistocene sediments would be about three times more than in Ludwigshafen; therefore the temporal resolution will be increased by the same amount. Furthermore, the results of the reflection seismic surveys and the pollen data are promising, regarding the completeness of the profile. The interglacials – Cromerian, Bavelian, Waalian, and Tiglian – could already be identified by a first scan of the pollen assemblages. To some extent the cores reveal strong and fast changes of the accommodation space and sediment supply ratio. The mostly-fluviatile character of the depositional environment was temporarily interrupted by lacustrine periods.

To close the gap of seismic information in the centre of the Heidelberg Basin and to ensure that the boreholes reveal thick and more or less complete sediments, geophysical pre-site surveys were conducted at the Viernheim and the Heidelberg borehole locations (Buness, Gabriel & Ellwanger 2008). In close relation to this project, the first gravity map of the Upper Rhine Graben that comprises all available French and German data was compiled (Rotstein et al. 2006). This map clearly images the course of the Upper Rhine Graben by the occurrence of negative gravity anomalies, of which the strongest is observed in the area around Heidelberg. This could be an indicator for a sediment succession of unusual large thickness. Furthermore, in the vicinity of the borehole Heidelberg UniNord reflection seismic profiles were recorded of which one N-S profile contributed significantly to the decision about the location for the borehole (Buness, Gabriel & Ellwanger 2008). This profile imaged for the first time a sub basin within the Heidelberg Basin. The usefulness of a seismic pre-site survey was also well demonstrated by the investigations around the borehole in Viernheim. Without the seismic information the borehole would have penetrated a fault at only 200 m depth – something that should be avoided with regard to the goals of this project. Based on the results of the seismic surveys, the borehole location could be relocated by several hundred meters.

One of the challenges of this project is the correlation between the three locations of the new boreholes, and beyond this, the correlation with additional, shallower boreholes in the area of the Heidelberg Basin. In addition to lithostratigraphic or biostratigraphic approaches results from geophysical downhole logging can also reveal additional insight into the sedimentary system. Downhole logging data is of particular value, wherever core quality is low or – even worse – core is not recovered, because it provides in-situ information about the sediment successions. Hunze & Wonik (2008) discuss the physical properties of the different lithologies on the basis of logging data and suggest a hole-to-hole correlation between several locations in the Heidelberg Basin. Furthermore, by statistical analysis of specific data sets additional information about sediment provenance could be derived. With sediments deposited by the rivers Rhine and Neckar, two main sediment provenances could be distinguished.

Facing the challenge of stratigraphic correlation, but also that of climate reconstruction, Wedel (2008) analysed core material from both the Viernheim and Ludwigshafen locations with regard to their fossil content, and particularly the remains of molluscs. The potential for the preservation of molluscs is highly variable. Fossils are often found in the argillaceous layers of the fine-grained horizons (Zwischenhorizonte), and to a minor amount also in the fine and medium-grained sand fraction of the coarse-grained horizons (Kieslager). The Pliocene beds do not contain any significant remnants of molluscs. Especially from a Mid-Pleistocene horizon, distinct information about several interglacials can be revealed that are suitable for correlation with pollen data and a reconstruction of the palaeo-environment. As a highlight, two mollusc species and one rodent species from the Lower Pleistocene (Lower Biharium) were identified in the northern Upper Rhine Graben for the first time.

First pollen spectra from the research borehole Heidelberg UniNord 1 are discussed by Hahne, Ellwanger & Stritzke (2008). Although only four short sections with well-preserved pollen were found, with the evidence for a Waalian thermomer, a first biostratigraphic marker of regional relevance was found. The pollen spectrum derived from the peaty sequence between 180 and 181.7 m depth is very similar to the flora of the type-locality for the Waalian (the Leerdam section in the Netherlands), both in pollen genera and quantities. Especially the occurrence of *Tsuga* strengthens the interpretation as Waalian. From these first findings a uniform forest vegetation in Mid Europe for the early Pleistocene is concluded, representing a climate that was not warmer than today.

In future, correlation between all the available boreholes must be based on a combination of several independent observations. Beside geophysical data and palynological data, absolute geochronological data is required especially. Unfortunately, no dating method is available that can be applied to the entire Quaternary age spectrum. Young sediments (up to ~150 ka) can be dated by applying luminescence dating techniques. Although in the meantime some few and unpublished results are available for the new cored-boreholes in the Heidelberg Basin (pers. communication Lauer), the method has been tested before with fluviatile sediments of the Bremgarten section in the southern part of the Upper Rhine Graben (Frechen et al. 2008). The results prove that OSL dating is a suitable method for fluviatile sediments from large river systems. Insufficient bleaching of the sediments prior to deposition seems to be not as dramatic as previously thought. The most important finding for the Bremgarten section is a short period of major erosion and re-sedimentation of fluvial sediments from the „Tiefgestade" at the Bremgarten section between 500 and 600 years before present, which correlates with the begin of the Little Ice Age ca. AD 1450. Likewise interesting results are expected for the Heidelberg Basin Drilling Project in the future.

This special issue on the Heidelberg Basin Drilling Project is published at an early stage of a just-starting joint research project that comprises aspects from many geoscientific disciplines. The intention of this issue is to make some main results already available to the geoscientific community, e.g. the reflection seismic data or the lithologs of the new-cored boreholes. In fact, detailed analytic investigation of the core material has not begun. Therefore, a uniform interpretation of the three borehole locations cannot be presented, which becomes especially obvious with the use of the terms „Base Quaternary" or „transition Plio-Pleistocene". But the cored boreholes should provide unique material to solve these challenges during the next years. Some aspects of this study have been submitted as a proposal to the German Research Foundation in 2008.

These eight contributions to this special issue of the Quaternary Science Journal (Eiszeitalter und Gegenwart) present the most recent findings from ongoing research on the Heidelberg Basin. Thereby, they complement some papers dealing with „The Rhine – a major fluvial record", which is the title of a special issue of the Netherlands Journal of Geosciences published in 2008, edited by Wim Westerhoff. This special issue addresses, for instance, issues like the tectonic influence on the preservation of fluviatile sediments (Weidenfeller & Kärcher 2008), palynological investigations (Knipping 2008), heavy mineral analysis (Hagedorn & Boenigk 2008), and rock and paleomagnetic studies (Rolf, Hambach & Weidenfeller 2008).

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Drilling projects are always challenging tasks, requiring support from many persons and institutions. The Heidelberg Drilling Project profited significantly from the support of actual and former heads of the involved institutions, namely Prof. Dr. U. Yaramanci, Prof. Dr. H.-J. Kümpel, Prof. Dr. R. Watzel, Ltd. Bergdirektor V. Dennert, Prof. Dr. B. Stribrny, Dr. R. Becker, and Prof. Dr. H. Ehses. The cores from the Ludwigshafen-Parkinsel boreholes were made available by Technische Werke Ludwigshafen. Logistic support was given by the University of Heidelberg, who provided the piece of land for the Heidelberg UniNord 1 borehole, Helmut Huber and the Amt für Vermögen und Bau Baden-Württemberg, Mannheim, who made the piece of land for the Heidelberg UniNord 2 borehole available, and the Springer publishing group. Dr. E. Würzner, Lord Major of the city of Heidelberg, and Dr. R. Franke, Stadtwerke Viernheim, arranged contacts, whenever necessary. The involved members of staff of the Amt für Umweltschutz Heidelberg and the Universitätsbauamt Heidelberg were always interested in the project and helped in a friendly way wherever they could. All this support is gratefully acknowledged.

Prerequisite for this special issue about the Heidelberg Basin Drilling Project was the offer from Holger Freund as editor of Quaternary Science Journal (Eiszeitalter und Gegenwart) to publish a special issue. He organised the review process with great patience. But the most important work was done by the many authors who contributed with their papers to this issue. The corresponding comments of many reviewers helped to improve these papers. Many thanks to all colleagues involved!

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Vorwort: Das Bohrprojekt „Heidelberger Becken“

Gerald Gabriel, Dietrich Ellwanger, Christian Hoselmann & Michael Weidenfeller

Seit dem späten Pliozän / frühen Pleistozän stellt der Rhein als einer der größten europäischen Flüsse das einzige Entwässerungssystem dar, welches die Alpen mit der Nordsee verbindet. Auf seinem Verlauf von den Alpen bis hin zum Ärmelkanal passiert er unterschiedliche geomorphologische und geologische Einheiten, von denen der Oberrheingraben die Hauptsedimentfalle bildet (Abb. 1). Während die alpinen Vorlandbecken aufgrund der hohen Dynamik des Gesamtsystems nur ein geringes Erhaltungspotenzial hinsichtlich der Sedimentablagerung aufweisen, und das Ablagerungsgebiet unmittelbar an der Nordseeküste mehrfach signifikant durch pleistozäne Meeresspiegelschwankungen beeinflusst wurde, bietet die andauernde Subsidenz des Oberrheingrabens einmalige Bedingungen für die kontinuierliche Akkumulation von Sedimenten. Die beiden größten Sedimentfallen sind dabei das Geiswasser Becken im südlichen Teil sowie das Heidelberger Becken im Nordosten. Generell nimmt die mittlere Korngröße der im Oberrheingraben abgelagerten alpinen Sedimente von Süden nach Norden ab. Das Heidelberger Becken fungiert als distale Falle im Oberrheingraben für alpine Sedimente, die durch den Rhein Richtung Norden transportiert werden. Hier ist die kontinuierliche Ablagerung von Sedimenten weniger stark durch Diskontinuitäten gestört als im südlichen Teil des Rheingrabens. Daher stellt das Heidelberger Becken eine Schlüsselposition für das Verständnis der glazialen Entwicklung der Alpen seit dem späten Pliozän und darüber hinaus für einen Vergleich mit der glazialen Entwicklung Nordeuropas dar (Ellwanger et al. 2005).

Das Heidelberger Becken enthält eine der mächtigsten Abfolgen plio-/pleistozäner Sedimente im kontinentalen Mitteleuropa. Die Radium Sol Therme Bohrung, welche zwischen 1913 und 1918 im Zentrum von Heidelberg abgeteuft wurde, wird in der Literatur bis heute kontrovers diskutiert. Die „Quartärbasis“ wird in Tiefen von 382 m (Bartz 1951), 400 m (Salomon 1927) oder sogar 650 m (Fezer 1997) gesehen. Durch umfassende reflexionsseismische Messungen ist heute belegt, dass die quartären Ablagerungen Mächtigkeiten größer 300 m erreichen. Da reflexionsseismische Untersuchungen jedoch nur in der Umgebung von Heidelberg durchgeführt wurden, nicht jedoch im Stadtgebiet selbst, waren bislang keine detaillierten Informationen über quartäre Strukturen in diesem Bereich verfügbar.

Mit dem Ziel, zu einem tieferen Verständnis hinsichtlich der geologischen Entwicklung des Heidelberger Beckens, insbesondere der Steuerung durch Klimaveränderungen und Tektonik, sowie der Korrelation der alpinen und nordeuropäischen Vereisungsgeschichte zu gelangen, wurde das Bohrprojekt „Heidelberger Becken“ durch das Leibniz-Institut für Angewandte Geophysik (LIAG – vormals Institut für Geowissenschaftliche Gemeinschaftsaufgaben, GGA-Institut) und die drei geologischen Dienste von Baden-Württemberg, Hessen und Rheinland-Pfalz initiiert. Das Projekt fokussiert auf die Beckenentwicklung seit dem späten Pliozän. Die Untersuchungen basieren wesentlich auf neuen Kernbohrungen an drei verschiedenen Lokationen innerhalb des Heidelberger Beckens, welche unterschiedliche Faziesräume abbilden (Abb. 2). Zwei 300 m tiefe Kernbohrungen in Ludwigshafen – abgeteuft 2002 und 2006 – repräsentieren den westlichen Rand des Beckens. Diese Bohrungen wurden im Rahmen der Grundwassererkundung realisiert und dem Geologischen Dienst von Rheinland-Pfalz zur Verfügung gestellt. Die 350 m tiefe Kernboh-

Abb. 1: Das Heidelberger Becken (HDB) im Geosystem „Rhein“ (verändert nach ELLWANGER et al. 2003, 2005).

- Kleine Karte: Der Oberrheingraben als Hauptsedimentfalle des Rheins zwischen Alpen und Nordsee.
- Große Karte: Verschiedene Landschaftstypen entlang des Rheins von den Alpen bis zum Oberrheingraben.

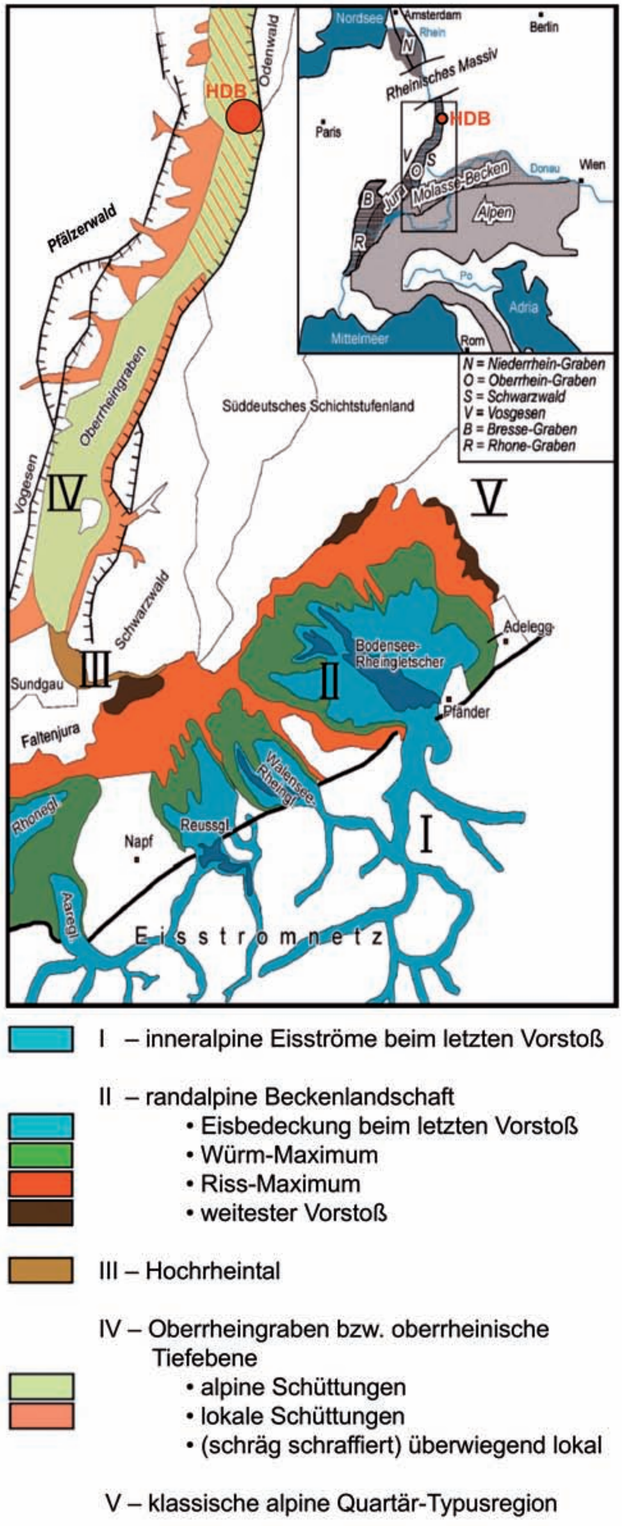
I – Inneralpine (übertiefe) Täler und die Eisströme beim letzten Vorstoß.

II – Randalpine Becken- und Seenlandschaft mit verschiedenen Eisrandlagen und der Eisbedeckung beim letzten Vorstoß.

III – Hochrheintal, Terrassenstufen und verschüttete Täler.

IV – Oberrheingraben bzw. oberrheinische Tiefebene, Lockersedimente im Südteil überwiegend alpiner Herkunft, im Nordteil (schräg schraffiert) überwiegend lokaler Herkunft (Schwarzwald, Vogesen).

V – Die klassische oberschwäbische Schmelzwasserterrassenlandschaft (Typregion für Würm, Riss, Mindel und Günz).



Tab. 1: Lithostratigraphische Einheiten, wie sie durch die drei Geologischen Dienste verwendet werden, welche Anteile am Heidelberger Becken haben.

<table>
<tr><th colspan="2">Baden-Württemberg
Symbolschlüssel Geologie Baden-Württemberg</th><th>Rheinland-Pfalz
Weidenfeller & Kärcher 2008
Weidenfeller & Knipping 2008</th><th>Hessen</th><th rowspan="2">Bartz 1982</th></tr>
<tr><td colspan="2"></td><td></td><td>Äolische Sande (Pleistozän bis Holozän)</td></tr>
<tr><td colspan="2">Mannheim-Formation</td><td>Oberes Kieslager (OKL)</td><td>Sand-Kies Lagen
Neckar-dominiert, wenig alpin</td><td>Oberes Kieslager (OKL)
Grobsedimente (alpin und lokal)</td></tr>
<tr><td rowspan="4">Kurpfalz-Formation</td><td>Ladenburg Horizont</td><td>Oberer Zwischenhorizont (OZH)</td><td>Zwischenhorizont
vorwiegend feinklastische Sedimente</td><td>Obere Zwischenschicht (OZ)
nur Feinsedimente</td></tr>
<tr><td rowspan="3">Weinheim Schichten</td><td>Mittlere sandig-kiesige Folge</td><td rowspan="3">Wechsel von
Sand-(Kies) Lagen häufig in "Rheinischer Fazies" und
feinklastischen Zwischenhorizonten
(alpine) Rheinsedimente, wenig Neckar</td><td>Mittleres Kieslager (MKL)
Grobsedimente (alpin und lokal)</td></tr>
<tr><td>Unterer Zwischenhorizont (UZH)</td><td>Untere Zwischenschicht (UZ)
nur Feinsedimente</td></tr>
<tr><td>Untere sandig-siltige Folge</td><td>Unteres Kieslager (UKL)
Grobsedimente (alpin und lokal)
Altquartär 1 und 2 (AQ1 und AQ2)*
Übergangsbereich mit ersten alpinen Sedimenten</td></tr>
<tr><td colspan="5">Wechsel des Hauptliefergebietes</td></tr>
<tr><td colspan="2">Iffezheim-Formation</td><td>Ton-Sand-Silt Folgen</td><td>Ton-Silt und Sand Lagen
Sedimente lokalen Ursprungs</td><td>Pliozän I-III *
Sedimente lokalen Ursprungs</td></tr>
</table>

* eher die Bezeichnung eines Sedimenttyps, denn eine strenge geochronologische Einordnung

rung bei Viernheim soll Informationen über die zentrale Beckenfazies liefern. Diese im Sommer 2006 abgeschlossene Bohrung wurde durch den Geologischen Dienst von Hessen betreut und finanziert. Die letzte Kernbohrung, Heidelberg UniNord, wurde im Subsidenzzentrum des Beckens am östlichen Rand des Oberrheingrabens angesetzt. Diese durch das Leibniz-Institut für Angewandte Geophysik und den Geologischen Dienst von Baden-Württemberg finanzierte Bohrung hat ihre Endteufe von 500 m im Juli 2008 erreicht. Alle neuen Kernbohrungen zusammen liefern 1450 m Kernmaterial, das nun für ein detailliertes Untersuchungsprogramm zur Verfügung steht.

Bislang existiert in den Bundesländern mit Anteilen am Heidelberger Becken (Baden-Württemberg, Hessen und Rheinland-Pfalz) keine einheitliche Gliederung der plio-/pleistozänen Ablagerungen. In jedem geologischen Dienst gibt es verbindliche Vorgaben, welche den spezifischen Gegebenheiten der lokalen Geologie Rechnung tragen. Die Geologie des südlichen Oberrheingrabens in Baden-Württemberg wird maßgeblich durch die Ablagerung grobklastischer Sedimente bestimmt, die in den Alpen abgetragen wurden. Daher wird eine Formationsgliederung angewendet, die im südlichen Graben die Hauptdiskontinuitäten und somit die Dynamik des Systems berücksichtigt (Symbolschlüssel Geologie Baden-Württemberg 2007). Dagegen basiert die in Hessen und Rheinland-Pfalz verwendete Terminologie zum Teil auf den von Bartz (1982) und durch die HGK (1999) eingeführten Systemen, die zwischen hydrogeologischen Einheiten unterscheiden. In diesem frühen Stadium des Projekts „Heidelberger Becken“ ist die Definition einer einheitlichen Nomenklatur noch nicht möglich. Tabelle 1 stellt die in diesem Themenheft verwendeten unterschiedlichen Gliederungen gegenüber.

Um diese Diskrepanzen zu überwinden, müssen die Untersuchungen im Projekt „Heidelberger

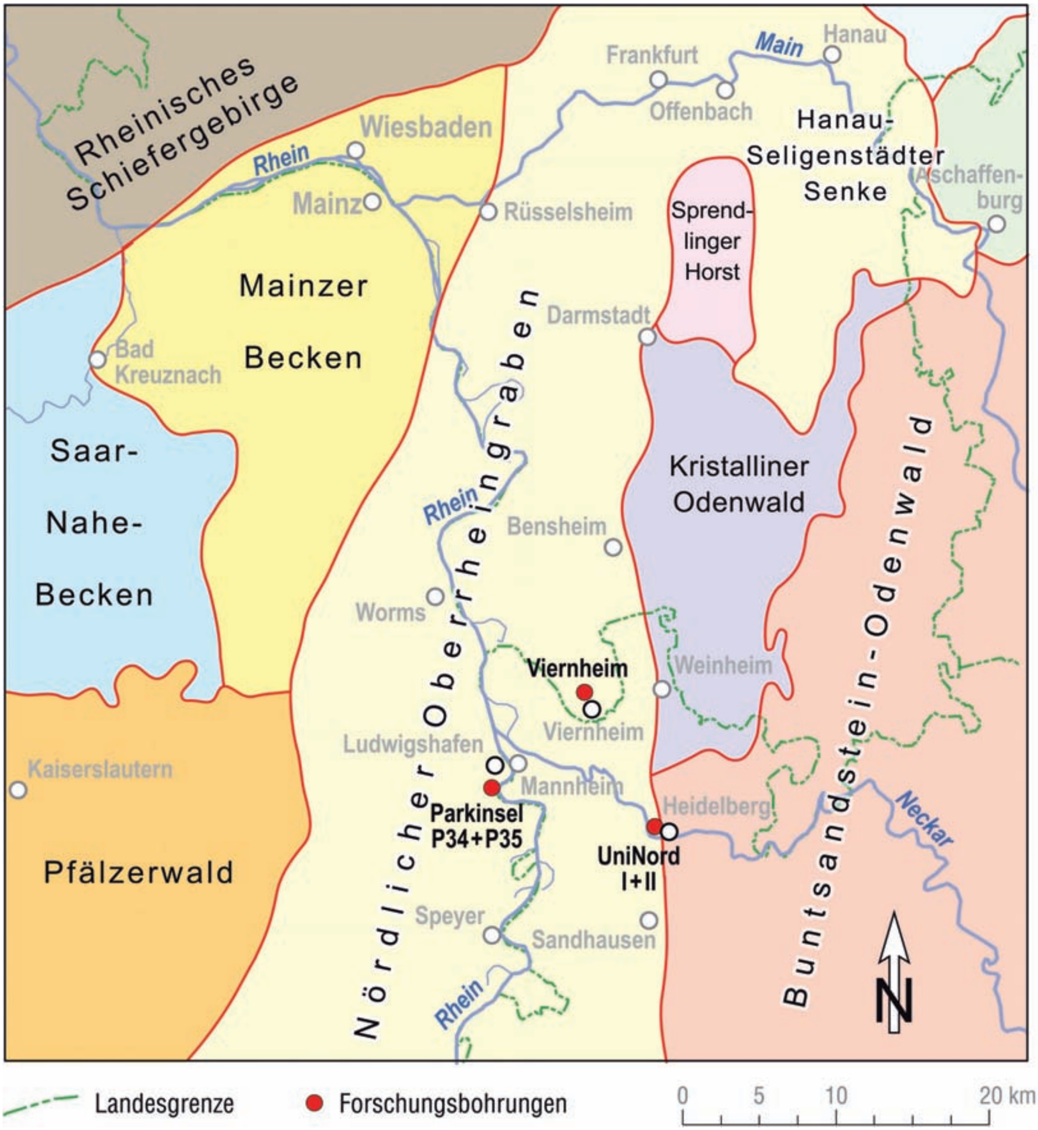


Abb. 2: Geologische Strukturräume mit den drei Bohrlokationen Ludwigshafen-Parkinsel (Kernbohrungen P34 und P35, jeweils 300 m tief), Viernheim (350 m tief) und Heidelberg UniNord (Forschungsbohrungen Heidelberg UniNord 1, 190 m tief und Heidelberg UniNord 2, 500 m tief) im Heidelberger Becken.

Becken“ zunächst auf die Erstellung eines Referenzprofils für das Gebiet nördlich der Alpen ausgerichtet sein. Dieses beinhaltet petrographische, sequenzstratigraphische, biostratigraphische und magnetostratigraphische Ansätze, die durch geochronologische und geophysikalische Daten ergänzt werden. Über diese lokalen bis regionalen Aspekte hinaus ist mit den neuen Bohrungen im Hinblick auf die Korrelation der glazialen Entwicklungen im Alpenraum und Nordeuropa ein Sedimentarchiv von überregionaler Bedeutung erschlossen worden. In diesem Zusammenhang sollen auch Proxy für Umweltveränderungen/Klimaveränderungen in der Vergangenheit abgeleitet werden. Diese Ziele können nur erreicht werden, weil die gebohrten Kerne eine hohe zeitliche Auflösung und nur wenige Schichtlücken aufweisen (Hoselmann et al. 2008). Die in diesem Themenheft vom Quaternary Science Journal (Eiszeitalter und Gegenwart) zusammengestellten Artikel zeigen, dass die gebohrten Kerne unter diesen Aspekten als nahezu ideal angesehen werden können.

Aufgrund der Verfügbarkeit der beiden Kernbohrungen in Ludwigshafen zu einem sehr frühen Zeitpunkt in diesem Projekt, liegt für diese Lokation aktuell der umfangreichste Datensatz vor. Weidenfeller & Knipping (2008) präsentieren sich ergänzende konsistente Datensätze von Schwermineralanalysen, Pollenanalysen und der Kernbeschreibung selbst. Etwas überraschend unterscheiden sich die Ergebnisse der beiden Bohrungen Ludwigshafen-Parkinsel P34 und P35 in einzelnen Aspekten signifikant, obwohl beide Lokationen nur etwa 500 m auseinander liegen. Während die oberen Abschnitte beider Bohrungen gut korrelieren, sind die Mächtigkeiten einzelner Einheiten des unteren Teils lateral sehr variabel. Selbst der Übergang Plio-/Pleistozän wurde in unterschiedlichen Teufen angetroffen. Folglich erscheint diese Region während des späten Pliozäns/frühen Pleistozäns maßgeblich durch Tektonik beansprucht worden zu sein. Diese Ergebnisse belegen, dass die Ableitung der klimatischen und fluviatilen Entwicklung einer Region unsicher ist, sofern diese nur auf einer Bohrung beruht. Die Sedimente werden nicht nur durch die fluviatile Dynamik beeinflusst, sondern auch durch kleinmaßstäbliche tektonische Ereignisse. Die auf verschiedenen unabhängigen Untersuchungen, insbesondere auch Pollenanalysen, basierende Charakterisierung und stratigraphische Einordnung der Sedimente ist grundlegende Voraussetzung für eine verlässliche Interpretation der durch Klima und Tektonik gesteuerten Ablagerungsgeschichte.

Unter Berücksichtigung des bislang vorliegenden Datensatzes ergibt sich für die Bohrung Viernheim ein Bild, das dem in Ludwigshafen sehr ähnlich ist (Hoselmann 2008). Auf Schwermineralanalysen, Karbonatgehalten und der Petrographie basierend, wird der Übergang Plio-/Pleistozän bei 225 m gesehen. Allerdings handelt es sich dabei um keinen scharfen Übergang, sondern um einen Bereich aufgearbeiteter Horizonte. Die pleistozäne Sedimentabfolge wird durch alpines Material dominiert, lokale Ablagerungen des Neckars treten nur untergeordnet auf. Der wesentliche Teil des pleistozänen Abschnitts wird aus zehn sich wiederholenden Abfolgen aufgebaut, welche mit kiesig-sandigen Lagen beginnen und mit schluffig-tonigen Sedimenten enden. Aufgrund noch fehlender Pollenanalysen kann bislang keine detaillierte Korrelation mit den Bohrungen in Ludwigshafen vorgenommen werden. Jedoch stellt Hoselmann (2008) basierend auf Leithorizonten, wie dem ersten Auftreten der „Rheinischen Fazies“, erste Korrelationen mit weiteren Bohrungen aus der Region Viernheim-Bensheim vor. Wenngleich der generelle Trend einer Zunahme der Mächtigkeit der rheinischen Fazies zum Zentrum des Heidelberger Beckens hin aufgezeigt werden kann, wird auch das fundamentale Problem der erschwerten Korrelation infolge an bestimmten Lokationen fehlender einzelner Schichtpakete angesprochen.

Die Heidelberg UniNord Bohrung wurde erst Ende Juli 2008 fertig gestellt (Ellwanger et al. 2008). Basierend auf den Ergebnissen der reflexionsseismischen Erkundung und der alten Bohrung Radium Sol Therme wird davon ausgegangen, dass diese Lokation das Depozentrum des Heidelberger Beckens repräsentiert. Diese Annahme scheint durch die ersten palynologischen Daten bestätigt zu werden. Selbst in 420 m Teufe ist das Pollenspektrum noch quartärzeitlich. Sollte sich dieses Ergebnis zukünftig durch detaillierte Untersuchungen erhärten, wäre die Mächtigkeit der pleistozänen Sedimente an dieser Lokation etwa dreifach so groß wie in Ludwigshafen und es würde sich die erwartete hohe zeitliche Auflösung bestätigen. Darüber hinaus werden die Ergebnisse der reflexionsseismischen Messungen und der Pollendaten als viel versprechend im Hinblick auf die Vollständigkeit des Profils angesehen. Bereits bei der ersten Durchsicht der Pollenspektren konnten die Interglaziale Cromer, Bavel, Waal und Tiglium identifiziert werden. Die Bohrkerne zeigen teilweise starke und auch schnelle Änderungen im Verhältnis von Akkommodationsraum zu Sedimentangebot. Der meist fluviatil geprägte Ablagerungsraum wird zeitweise von lakustrinen Perioden abgelöst.

Um die Lücke an seismischen Informationen im Zentrum des Heidelberger Beckens zu schließen und sicher zu stellen, dass die Bohrungen mächtige und vergleichsweise vollständige Sedimente erschließen, wurden an den Bohrlokationen Viernheim und Heidelberg UniNord geophysikalische Vorerkundungen durchgeführt (Buness, Gabriel & Ellwanger 2008). In enger Verknüpfung mit diesem Projekt wurde die erste Schwerekarte des Oberrheingrabens erstellt, die sämtliche verfügbaren Daten von französischer und deutscher Seite berücksichtigt (Rotstein et al. 2006). Diese Karte bildet durch das Auftreten negativer Schwereanomalien deutlich den Verlauf des Oberrheingrabens ab, von denen die größte im Bereich um Heidelberg zu beobachten ist. Dies kann als Hinweis auf Sedimentabfolgen von ungewöhnlich großer Mächtigkeit angesehen werden. Ferner wurden im Umfeld der Bohrung Heidelberg UniNord reflexionsseismische Profile aufgenommen, von denen ein N-S Profil maßgeblich zur Festlegung des Bohrpunktes beigetragen hat (Buness, Gabriel & Ellwanger 2008). Dieses Profil bildet zum ersten Mal ein Subbecken im Heidelberger Becken ab. Der Mehrwert einer seismischen Vorerkundung wurde ebenfalls durch die Untersuchungen rund um die Bohrlokation bei Viernheim demonstriert. Ohne die seismischen Informationen hätte die Bohrung bereits in einer Tiefe von 200 m eine Störung durchteuft – ein Sachverhalt, der im Hinblick auf die Ziele dieses Projekts unbedingt vermieden werden sollte. Die Ergebnisse der seismischen Messungen berücksichtigend konnte der Bohransatzpunkt somit um einige hundert Meter verschoben werden.

Eine der Herausforderungen in diesem Projekt liegt sicherlich in der Korrelation zwischen den drei Lokationen der neuen Bohrungen sowie darüber hinaus in der Korrelation mit weiteren, weniger tiefen Bohrungen im Bereich des Heidelberger Beckens. In Ergänzung zu lithostratigraphischen oder biostratigraphischen Ansätzen können auch bohrlochgeophysikalische Messungen Einblicke in das sedimentäre System liefern. Bohrlochgeophysikalische Daten sind dort von besonderem Wert, wo die Kernqualität schlecht ist, oder – noch ungünstiger – keine Kerne gewonnen werden konnten, da sie in-situ Informationen über die Sedimentabfolgen zur Verfügung stellen. Hunze & Wonik (2008) diskutieren die physikalischen Eigenschaften der verschiedenen Lithologien auf der Basis von Bohrlochmessungen und schlagen eine Korrelation zwischen verschiedenen Bohrpunkten im Heidelberger Becken vor. Darüber hinaus werden durch die Anwendung statistischer Verfahren auf spezifische Datensätze Informationen bezüglich der Liefergebiete der Sedimente abgeleitet. Mit Sedimentablagerungen durch den Rhein bzw. den Neckar können zwei unterschiedliche Liefergebiete unterschieden werden.

Ebenfalls die stratigraphische Korrelation betreffend, aber auch Aspekte der Paläo-Klimarekonstruktion, analysiert Wedel (2008) Kernmaterial der Bohrungen Viernheim und Ludwigshafen unter paläontologischen Aspekten, insbesondere im Hinblick auf Molluskenreste. Das Erhaltungspotenzial für Mollusken erscheint hochgradig variabel. Fossilien werden oftmals in den lehmig/tonigen Schichten der feinkörnigen Lagen (Zwischenhorizonte) gefunden, untergeordnet auch in den feinen und mittelfeinen Sanden der grobkörnigen Ablagerungen (Kieslager). In den pliozänen Ablagerungen finden sich keinerlei Molluskenreste. Eindeutige Informationen über mehrere Interglaziale können insbesondere aus einem Horizont entnommen werden, welcher dem mittleren Pleistozän zugeordnet wird. Diese Daten sind sowohl für die Korrelation mit Pollenanalysen als auch für die Rekonstruktion der Paläo-Umweltbedingungen geeignet. Ein „Highlight“ stellt der erstmalige Fund von zwei Molluskenarten sowie einer Nagetierart im nördlichen Oberrheingraben aus dem unteren Pleistozän (Unteres Biharium) dar.

Hahne, Ellwanger & Stritzke (2008) diskutieren erste Pollenanalysen der Forschungsbohrung Heidelberg UniNord 1. Wenngleich gut erhaltene Pollen lediglich in vier kurzen Abschnitten aufgefunden wurden, konnte mit der Identifikation der Waal-Warmzeit ein biostratigraphischer Marker bestimmt werden, der auch überregional von Bedeutung ist. Das der torfigen Sequenz zwischen 180,0 und 181,7 m zugehörige Pollenspektrum ähnelt sowohl hinsichtlich der Pollentypen als auch der Pollenhäufigkeit stark der Flora des Typus-Profils für das Waalium (Profil Leerdam, Niederlande). Insbesondere das Auftreten von *Tsuga* bedingt die Einordnung in die Waal-Warmzeit. Basierend auf diesen ersten Ergebnissen wird eine einheitliche Bewaldung Mitteleuropas im Zeitraum des frühen Pleistozäns postuliert, die ein Klima repräsentiert, das nicht wärmer war als das heutige.

Korrelationen zwischen den verschiedenen Bohrungen müssen zukünftig auf der Kombination der verschiedenen unabhängigen Verfahren aufbauen. Neben geophysikalischen und palynologischen Daten sind vor allem absolute Altersdatierungen notwendig. Leider steht kein Datierungsverfahren zur Verfügung, welches auf das gesamte Quartär angewendet werden kann. Junge Sedimente (bis zu ~150 ka) können mit Lumineszenztechniken datiert werden. Obwohl inzwischen auch erste unpublizierte Ergebnisse für die neuen Kernbohrungen im Heidelberger Becken vorliegen (Lauer, pers. Mitteilung), wurde die Methode zunächst an fluviatilen Sedimenten des Profils Bremgarten aus dem südlichen Teil des Oberrheingrabens getestet (Frechen et al. 2008). Die Ergebnisse zeigen, dass OSL-Techniken für die Datierung fluviatiler Sedimente großer Flusssysteme geeignet sind. Eine ungenügende Bleichung der Sedimente vor der Ablagerung scheint weniger großen Einfluss auf die Ergebnisse zu haben, wie bislang angenommen. Das wesentliche Ergebnis hinsichtlich des Profils Bremgarten besteht in der Ermittlung eines kurzen Abschnitts starker Erosion und Resedimentation fluviatiler Sedimente des Tiefegestades vor 500 bis 600 Jahren. Dieses Ereignis korreliert mit dem Beginn der kleinen Vereisung etwa 1450 AD. Ähnlich interessante Datierungsergebnisse sind zukünftig im Rahmen des Bohrprojektes „Heidelberger Becken“ zu erwarten.

Dieses Themenheft über das Heidelberger Becken erscheint zu einem frühen Zeitpunkt eines gerade beginnenden Forschungsvorhabens, welches Aspekte diverser geowissenschaftlicher Disziplinen vereint. Die Intention besteht darin, verschiedene grundlegende Ergebnisse, wie die Daten der Reflexionsseismik oder die Lithologs der neuen Kernbohrungen, der geowissenschaftlich arbeitenden Gemeinschaft verfügbar zu machen. Tatsächlich fehlen noch verschiedene detaillierte Untersuchungen am Kernmaterial. Daher kann zum jetzigen Zeitpunkt keine gemeinsame Interpretation des gesamten Kernmaterials vorgestellt werden, was sich insbesondere in der unterschiedlichen Verwendung der Begriffe „Quartärbasis“ oder „Übergang Plio-/Pleistozän“ niederschlägt. Mit den neuen Bohrkernen sollte aber einzigartiges Material zur Verfügung stehen, um diese Aufgabe in den kommenden Jahren lösen zu können. Ein Teil der Untersuchungen soll im Rahmen eines Antragpakets durchgeführt werden, welches 2008 bei der Deutschen Forschungsgemeinschaft eingereicht wurde.

Die acht Beiträge zu diesem Themenheft des Quaternary Science Journal (Eiszeitalter und Gegenwart) präsentieren die aktuellsten Ergebnisse andauernder Forschungsarbeiten zum Heidelberger Becken. Damit komplettieren sie verschiedene Artikel, welche sich mit dem „Rhein – ein bedeutendes fluviatiles Sedimentarchiv“ befassen. Dies ist der frei übersetzte Titel eines Sonderbands des Netherlands Journal of Geosciences, der 2008 unter der Editorenschaft von Wim Westerhoff publiziert wurde. Dieser Sonderband spricht ergänzende Themen, wie den Einfluss der Tektonik auf die Erhaltung fluviatiler Sedimente (Weidenfeller & Kärcher 2008), palynologische Untersuchungen (Knipping 2008), Schwermineralanalysen (Hagedorn & Boenigk 2008) sowie gesteins- und paläomagnetische Studien (Rolf, Hambach & Weidenfeller 2008) im Oberrheingraben an.

Dank

Bohrprojekte stellen stets eine herausfordernde Aufgabe dar, die Unterstützung vieler Personen und Institutionen verlangt. Das Bohrprojekt „Heidelberger Becken“ hat wesentlich von der Unterstützung der derzeitigen und früheren Leiter der beteiligten Einrichtungen profitiert, namentlich Prof. Dr. U. Yaramanci, Prof. Dr. H.-J. Kümpel, Prof. Dr. R. Watzel, Ltd. Bergdirektor V. Dennert, Prof. Dr. B. Stribrny, Dr. R. Becker und Prof. Dr. H. Ehses. Die Kernbohrungen Ludwigshafen-Parkinsel wurden durch die Technischen Werke Ludwigshafen zur Verfügung gestellt. Logistische Unterstützung gaben die Universität Heidelberg in Form der Bereitstellung des Grundstücks für die Bohrung Heidelberg UniNord 1, Helmut Huber sowie das Amt für Vermögen und Bau Baden-Württemberg mit der Bereitstellung des Geländes für die Bohrung Heidelberg UniNord 2 und der Springer-Verlag. Dr. E. Würzner, Oberbürgermeister der Stadt Heidelberg, und Dr. R. Franke, Stadtwerke Viernheim, vermittelten Kontakte, wo immer notwendig. Die beteiligten Mitarbeiter des Amts für Umweltschutz der Stadt Heidelberg und der Universität Heidelberg waren stets am Fortgang des Projekts interessiert und gaben jegliche Hilfe, die notwendig war. Für die gesamte Unterstützung herzlichen Dank!

Voraussetzung für dieses Themenheft über das Bohrprojekt „Heidelberger Becken“ war das Angebot von PD Dr. H. Freund als Editor von Quaternary Science Journal (Eiszeitalter und Gegenwart) einen Sonderband zu publizieren. Er organisierte mit großer Geduld das Begutachtungsverfahren. Die wichtigsten Arbeiten wurden jedoch durch die vielen Autoren durchgeführt, die mit ihren Artikeln zu diesem Themenheft beitragen. Die Anmerkungen der Gutachter gaben wesentliche Hinweise für die Verbesserung einzelner Manuskripte. Vielen Dank an alle Kollegen, die sich beteiligt haben!

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Correlation of Pleistocene sediments from boreholes in the Ludwigshafen area, western Heidelberg Basin

Michael Weidenfeller & Maria Knipping *)

Abstract: Cores from several boreholes in the Ludwigshafen area were analysed to investigate their sedimentology, palynology, palaeomagnetics, rock magnetics and heavy mineral composition. The preliminary results are presented from the new Ludwigshafen-Parkinsel borehole P35, which was drilled 500 m WSW of borehole P34, to a total depth of 300 m. Correlation between the two boreholes reveals similarities and dissimilarities in stratigraphy, structure and the thickness of the sediments. As a result of core documentation and the preliminary evaluation of the investigation results, a good correlation is established between the coarse and fine-grained sequences in both boreholes down to a depth of 122 m. However, the Plio-Pleistocene boundary in borehole P35 is much deeper than in P34. A fault throw of 42 m is assumed, attributable to young tectonics. The poor correlation between the thicknesses of the sediments in the lower sections of the two boreholes suggests that tectonism was particularly active in the Pliocene and Lower Pleistocene. The different occurrence of interglacial sequences in the two Ludwigshafen boreholes can be attributed to fluvial dynamics and neotectonic events. Further palynological analysis is required to determine whether the alternation of at least five interglacial periods determined in the Ludwigshafen-Parkinsel P34 borehole, can also be confirmed in the P35 borehole. The information gained so far from the correlation of the already analysed Middle Pleistocene interglacials in the Ludwigshafen/Mannheim area, as well as the links with the primarily Lower Pleistocene sections in Schifferstadt, already suggest that this would allow a much better understanding of the changes in vegetation and climate during the Pleistocene.

[Korrelation pleistozäner Sedimente aus Bohrungen im Raum Ludwigshafen, westliches Heidelberger Becken]

Kurzfassung: Im Raum Ludwigshafen wurden mehrere Kernbohrungen sedimentologisch, palynologisch, paläomagnetisch, gesteinsmagnetisch und schwermineralogisch untersucht. Erste Ergebnisse der neuen Bohrung Ludwigshafen-Parkinsel P35 werden vorgestellt, die 500 m WSW der Bohrung P34 bis 300 m abgeteuft wurde. Die Gegenüberstellung beider Bohrungen zeigt Übereinstimmungen, aber auch Unterschiede im Aufbau, Struktur und Mächtigkeit der Sedimente. Nach der Bohrkerndokumentation und ersten Auswertungen von Untersuchungsergebnissen lassen sich die grob- und feinkörnigen Sequenzen aus beiden Bohrungen bis in eine Teufe von 122 m gut miteinander korrelieren. Allerdings liegt die Plio-/Pleistozängrenze in der Bohrung P35 deutlich tiefer. Wahrscheinlich ist ein Versatzbetrag von 42 m anzunehmen, der auf junge Tektonik zurückzuführen ist. Die geringe Übereinstimmung der Mächtigkeiten in den tieferen Abschnitten der Bohrungen lässt vermuten, dass die Tektonik besonders im Pliozän und Unterpleistozän aktiv war. Die unterschiedliche Präsenz von warmzeitlichen Sequenzen in den beiden Ludwigshafener Bohrungen kann auf fluviale Dynamik und neotektonische Ereignisse zurückgeführt werden. Ob die in der Bohrung Ludwigshafen Parkinsel P34 erfassten Wechsel von mindestens 5 Warmzeiten auch in der Bohrung P35 bestätigt werden können, bleibt weiteren palynologischen Untersuchungen vorbehalten. Schon jetzt lässt die Korrelation zwischen den bereits bearbeiteten mittelpleistozänen Warmzeiten im Raum Ludwigshafen/Mannheim sowie die Verknüpfung mit den überwiegend altpleistozänen Abschnitten von Schifferstadt eine deutliche Kenntniserweiterung der pleistozänen Vegetations- und Klimaentwicklung erwarten.

Keywords: Upper Rhine Graben, Heidelberg Basin, Pleistocene, fluvial sediments, pollen analysis, neotectonics

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1 Introduction

To investigate hydrogeological aspects, numerous boreholes were cored in the Ludwigshafen/ Mannheim area in recent years. These cores were analysed using a wide range of methods (Fig. 1, Table 1). The results of the Ludwigshafen-Parkinsel P34 borehole in particular – which was drilled to a TD (total depth) of 300 m in 2002 with 95 % core recovery – provided a great deal of new information on the history of the river Rhine and the changes in vegetation and climate in the northern Upper Rhine Graben during the Pleistocene (Weidenfeller & Kärcher 2008). Of particular value were the palynological analyses (Knipping 2008), heavy mineral analyses (Hagedorn & Boenigk 2008) and the palaeomagnetic and rock-magnetic analyses (Rolf et al. 2008). This made it possible for the first time to reliably detect the Plio-Pleistocene boundary in the northern Upper Rhine Graben in a core, confirmed by various independent methods. Another core of 300 m (P35) was drilled approximately 500 m WSW from borehole P34 in 2006. P35 was analysed using a very similar range of methods. The results are presented in this paper, including a preliminary correlation between the two boreholes.

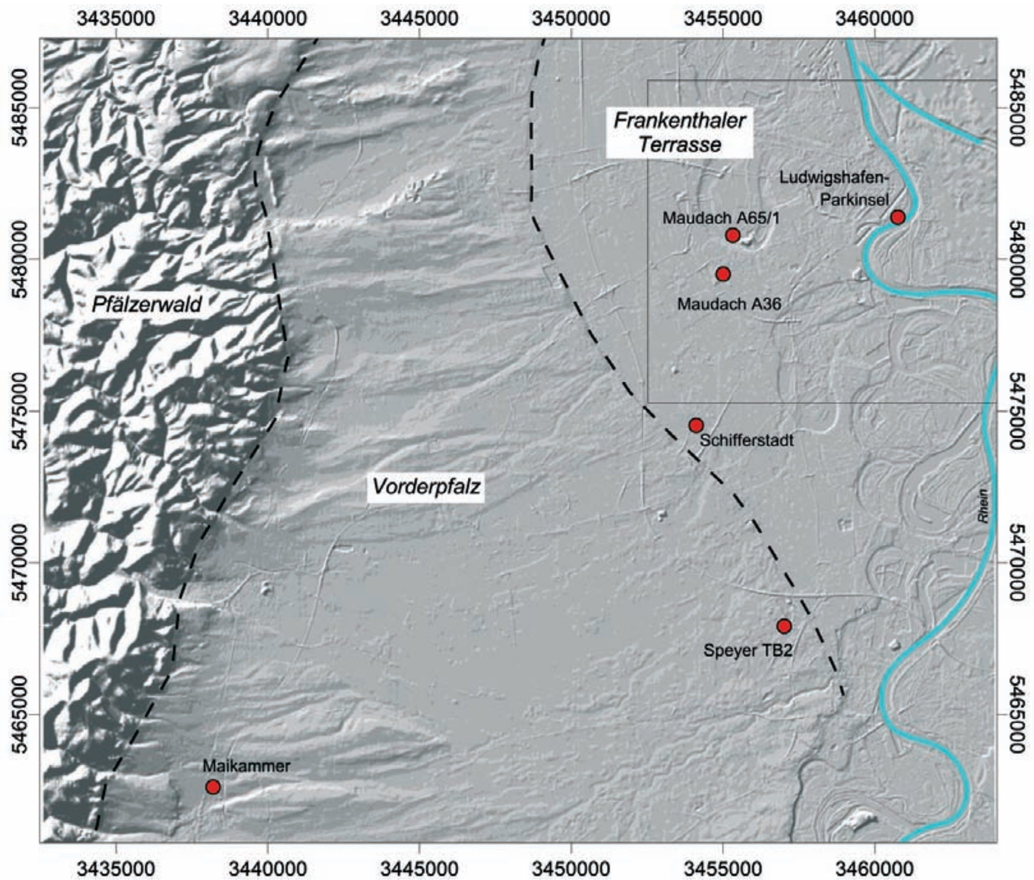

Fig. 1: Position of the investigated boreholes in the Vorderpfalz, on the Frankenthal Terrace and in the Ludwigshafen area.

Abb. 1: Lage untersuchter Bohrungen in der Vorderpfalz, auf der Frankenthaler Terrasse und im Raum Ludwigshafen.

The results of the P34 and P35 cores are the key for the interpretation of the unconsolidated sedimentary sequences in the Ludwigshafen/ Mannheim area. The sequences in both cores are characterised by alternating coarse-grained and fine-grained horizons. They are stratigraphically subdivided using a hydrogeological terminology (Bartz 1959, 1974, Kärcher 1987) into aquifers (Oberes Kieslager "OKL" (Upper Gravels) , Mittlere sandig-kiesige Folge (Middle Sandy-Gravely Series), Untere sandig-siltige Folge (Lower Sandy-Silty Series)) and Zwischenhorizonte (intermediate horizons) (Oberer Zwischenhorizont "OZH" (Upper Intermediate Horizon), Unterer Zwischenhorizont "UZH" (Lower Intermediate Horizon)). Reddish-brown sandy sediments were encountered in some sections and interpreted on the basis of heavy mineralogical analysis as fans deriving from the Pfälzerwald (Hagedorn 2004, Hagedorn & Boenigk 2008).

Whereas the stratigraphic position of the Lower Pleistocene sediments is uncertain, the upper gravels ("OKL") are conventionally attributed to a Weichselian age and referred to in the terminology of terrace division as a Lower

Table 1: Investigations of cores from boreholes Ludwigshafen-Parkinsel P34, P35 and Ludwigshafen-Maudach A36, TK 25 6516 Mannheim-Südwest

Tab. 1 : Untersuchungen an Kernen der Bohrungen Ludwigshafen-Parkinsel P34, P35 und Ludwigshafen-Maudach A36, TK 25 6516 Mannheim-Südwest

	Lu-Parkinsel P34	Lu-Parkinsel P35	Lu-Maudach A36
Coordinate (R-Wert)	34 60 666	34 60 230	34 54 850
Coordinate (H-Wert)	54 81 069	54 80 990	54 79 490
Depth	300 m	300 m	50.6 m
Surface	92 m NN	92 m NN	97 m NN
Description of the borehole sections	Weidenfeller (unpublished)	Weidenfeller (unpublished)	Weidenfeller (unpublished)
Lithofacies	Hagedorn (2004), Weidenfeller & Kärcher (2008)	this volume	-
Sedimentology	Kontny & Schulte (unpublished)	Sirocco & Schaber (unpublished)	-
Gamma Log	BLM, München (unpublished)	BLM, München (unpublished)	-
Thermal conductivity	-	Werner (2006)	-
Thin-section investigations	Menzies (2006)	-	-
Pollen analysis	Knipping (2008, in progress)	Knipping (in progress)	Knipping (in progress)
Heavy minerals	Hagedorn (2004), Hagedorn & Boenigk (2008)	Hoselmann (in progress)	-
Palaeomagnetic investigations/ Susceptibility/ rock magnetic investigations	Rolf et al. (2008)	Rolf & Hambach (in progress)	-
Clay mineralogy	-	Elsass et al. (in progress)	-
Molluscs	Wedel (2008)	Wedel (2008)	Wedel (2008)

terrace (Kärcher 1987). Accordingly, the interpretation of the upper aquitard (Oberer Zwischenhorizont "OZH") as an Eemian formation seems doubtful, which is confirmed by the research of Engesser & Münzing (1991), Rähle (2005) and Wedel (2008). Pollen analytical research by Knipping (2004, 2008) in the Mannheim area and on drillings at Schifferstadt (Fig. 1) and P34 indicates a Middle Pleistocene age (most probably Cromerian) for the OZH. Such positioning is further supported by palaeomagnetism measurements (Rolf et al. 2008), that indicate first reversal magnetism (780 ka, Matuyama-Brunhes boundary) to be positioned below the upper aquitard. The base of the Quaternary (Gauss-Matuyama boundary) at 177 m below surface in P34 is clearly deeper situated than in Schifferstadt and Speyer TB2 (Fig.1). This prompted Hagedorn (2004) to assume that the northeastern part of the central Graben block is being downthrown by active tectonism.

The rock magnetic investigations (Rolf et al. 2008) together with results of heavy mineral analyses (Hagedorn & Boenigk 2008) show a clearly structured sediment profile in P34. It was possible to identify the change from mainly locally controlled sedimentation of the graben margins to a more distinct alpine controlled sedimentation at a depth of 177 m (G/M-boundary) by magnetic data. Based on lithostratigraphic correlation with other sedimentary records from the URG and also based on palynological evidence, this event happened at the end of Late Pliocene during a time of normal polarity of the Earth's magnetic field (Gauss Chron?). The well-documented characteristic change in magneto-mineralogy from goethite to greigite almost at the same stratigraphic level, was interpreted solely as a climatic signal (Rolf et al. 2008) which can be correlated with the global climate change at ~2.5 Ma that is well documented in deep-sea sediments (Shackleton et al. 1984), loess deposits (Heller & Liu 1982) and fluvio-lacustrine sediments (Han et al. 1997).

The heavy mineral spectrum in the Pliocene sediments confirms that the only erosional material entering the Upper Rhine Graben came from the graben margins. Whether or not it is possible to subdivide the Pliocene sequences further depends on the results of additional investigations. In the uppermost Pliocene, the connection of the Palaeo-Rhine to the Alpine drainage system changed the heavy mineral spectrum of the Rhine sediments and led to a dominance of Alpine minerals (Hagedorn & Boenigk 2008). The boreholes drilled in the Ludwigshafen area revealed changes in the position of the river bed. Whilst the Rhine deposited sediments on the western margin of the northern graben during the Pliocene and at the beginning of the Quaternary, the river bed moved to further east during the subsequent period because the western margin is primarily dominated by sediments deriving from the Pfälzerwald. The situation further to the east is different because the sediments are dominated here by the Alpine heavy mineral spectrum. Because of the rapid subsidence of the eastern margin of the graben (Heidelberg Basin) it is conceivable that the bed of the river Rhine was located in this area of tectonic subsidence (Ellwanger et al. 2005). Renewed sedimentation by the Rhine in the western part of the northern Upper Rhine Graben did not start again before the deposition of the Upper Gravels during the Weichsellian glaciations, as seen on the Frankenthal Terrace (Weidenfeller & Kärcher 2008).

2 Results

The Upper Gravels (OKL) consist of arenaceous medium gravel to coarse gravel of up to 20 m in both cores. The OKL can be divided into two sections in both boreholes. The upper section consists of coarse gravel, extends in each case to a depth of 13 m, and is characterised by fining upwards from 10 m to 1 m depth. This is underlain by interbedded coarse sands and fine to medium gravels down to a depth of 19.5 m. A coarse-grained facies is only present in the Upper Gravels. The underlying sediments are distinctly finer grained (sandy-gravelly in the middle aquifer, and sandy-silty

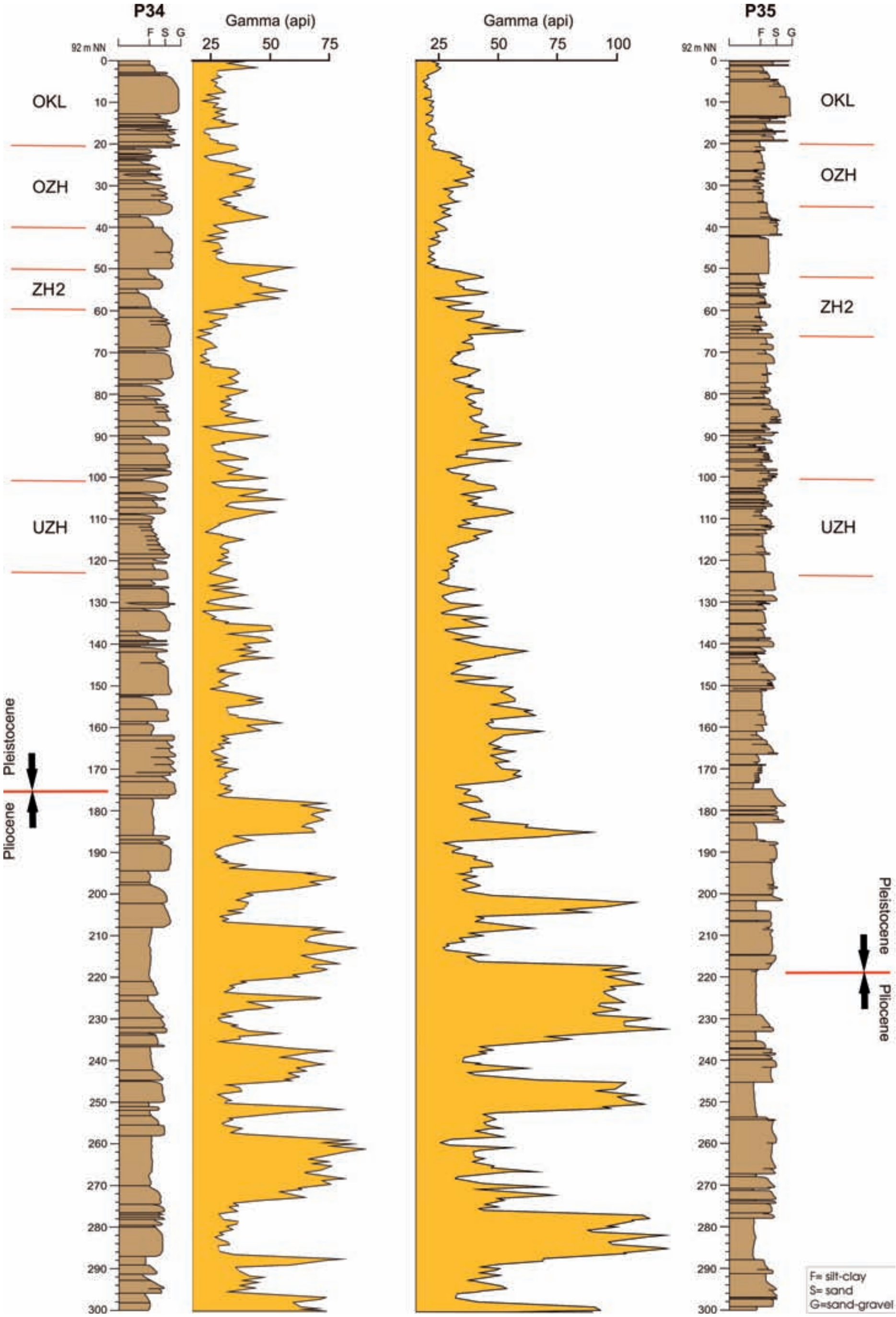

Fig. 2: Correlation of the lithofacies sections and Gamma Ray logs in the Ludwigshafen P34 and P35 boreholes.

Abb. 2: Gegenüberstellung der Lithofaziesprofile und Gamma-Logs der Bohrungen Ludwigshafen P34 und P35.

in the lower aquifer). The OKL is underlain by the Upper Intermediate Horizon (OZH) which is widely distributed in the northern Upper Rhine Graben, in the same way as the OKL. The OZH is located in borehole P34 between 21 m to 40 m, and in borehole P35 between 19.5 m to approximately 34 m depth (Fig. 2). The interbeds of the aquitard are clayey-silty and frequently contain organic intercalations of peat or turfy moulder.

The OZH in both boreholes is underlain to a depth of 101 m by a medium to coarse sandy sequence containing only subordinate and thin horizons of fine gravel. A silty-sandy intermediate horizon with interbedded organic horizons (ZH2) occurs in borehole P34 between 50 m and 60 m depth, and between 51 m and 66 m depth in borehole P35. This is followed by a medium to coarse sandy section which reaches a depth of approximately 87 m in both boreholes, underlain in P34 by fine-grained sediments with organic horizons down to a depth of about 92 m; and down to a depth of 98 m in P35. A distinct intermediate horizon, termed the Unterer Zwischenhorizont (Lower Intermediate Horizon) (UZH), occurs at a depth of 101 m to 122 m in both boreholes, and also contains several organic horizons. The sequence below 122 m is dominated by interbedded fine to medium-grained sand with intercalations of clayey-silty horizons. Borehole P35 has slightly thicker fine-grained sections between 151 m to 163 m, 167 m to 175 m, 183 m to 187 m and from 201,5 m to 204 m. According to the current status of the analysis, the fine-grained sections between 122 m to 183 m in borehole P35, are much thinner or completely absent in borehole P34. Coarser horizons with fine to medium gravel first occur between 162 m to 167 m in P34 and between 175 m to 183 m in P35.

There is a good correlation between the sediments in both boreholes from 0 m to 122 m depth – as also highlighted by a comparison of the Gamma Ray logs run in both boreholes (Fig. 2). This changes between 122 m to 183 m where the boreholes have different lithofacies profiles and Gamma Ray logs. The distinct change of the facies at 177 m depth in borehole P34, which is also interpreted as the Plio-Pleistocene boundary (Knipping 2008, Rolf et al. 2008), does not occur in borehole P35 until a depth of 183 m. The more than 10 m-thick fine-grained sequence lying beneath the Plio-Pleistocene boundary in P34 is absent at this depth in borehole P35, where it does not occur until a depth of 218 m to 232 m. The Gamma Ray logs at the same depths in both boreholes differ to a greater or lesser extent.

First analyses of the carbonate content and heavy minerals from isolated samples in borehole P35 (pers. com. C. Hoselmann, Hessisches Landesamt für Umwelt and Geologie) resulted in carbonate concentrations of 10 to 20 % down to a depth of 190 m and carbonate contents of up to 3 % between 190 m to 218 m (Fig. 3). The samples are non-calcareous beneath 218 m. The spectrum of transparent heavy minerals also reveals a difference in composition below a depth of 218 m. Garnet, epidote, alterite and hornblende dominate from 0 m to 218 m. Stable heavy minerals such as zircon and tourmaline are only present in subordinate amounts. The spectra are typical for sediments deposited in the Pleistocene Rhine. The sequences are interrupted – as also confirmed in the P34 borehole (Hagedorn 2004, Hagedorn & Boenigk 2008) – by sediments deposited by streams draining the Buntsandstein of the Pfälzerwald. These are characterised by heavy minerals dominated by tourmaline and higher concentrations of zircon. Below 218 m, tourmaline and zircon are joined by significant proportions of the TiO_2 group, as well as hornblende and garnet. Similar spectra occur in borehole P34 below the Plio-Pleistocene boundary. This characteristic later Pliocene heavy mineral spectrum is also shown in other boreholes drilled in the Northern Upper Rhine Graben, such as the Schifferstadt borehole (Hagedorn 2004) and in Viernheim (Hoselmann 2008).

Nearly 1200 samples were taken from the P34 cores for pollen analysis. 120 samples were initially selected for a preliminary analysis and prepared at the laboratory operated by LGB Rheinland-Pfalz. This preliminary analysis

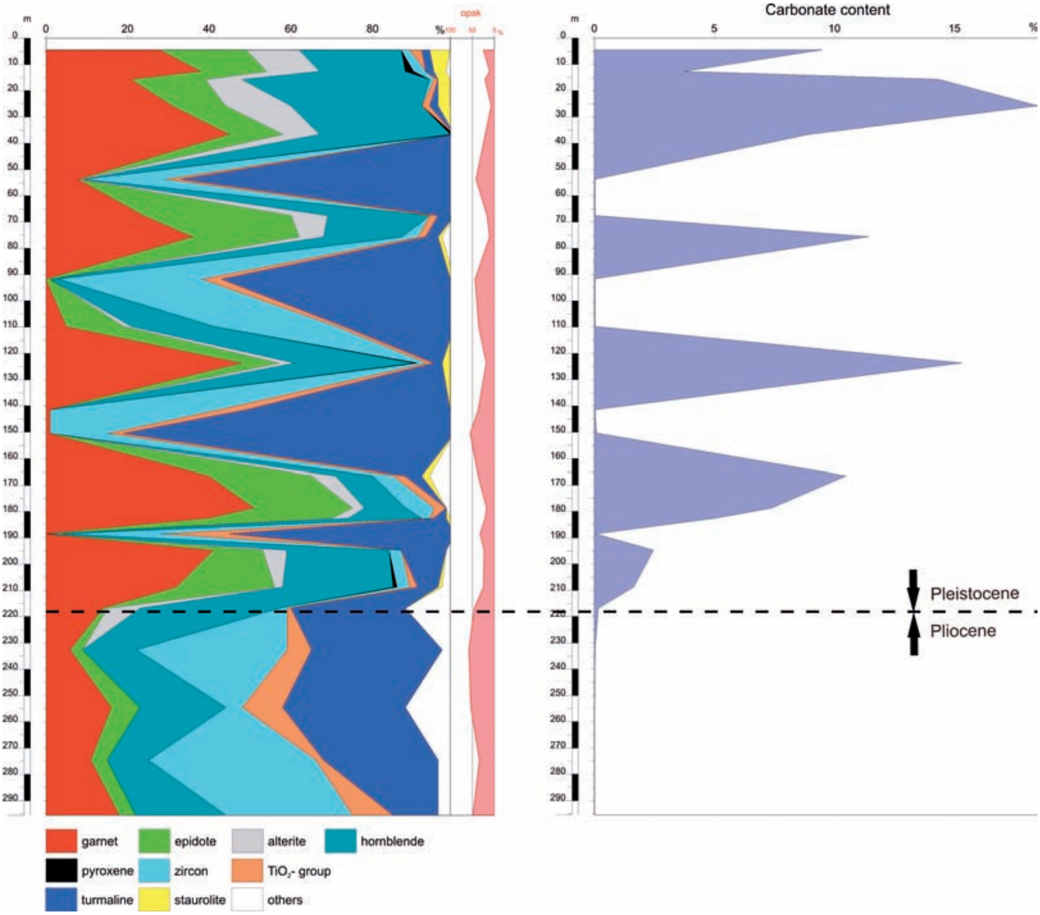

Fig. 3: Heavy mineral diagram and carbonate content of the Ludwigshafen P35 borehole (Hoselmann, pers. com.).

Abb. 3: Schwerminerale und Karbonatgehalt der Bohrung Ludwigshafen P35 (Hoselmann, pers. Mitt.).

involved a quick estimation of the pollen content, or counting only a minor number of pollen grains. 1600 pollen samples were taken from the P35 borehole, and 60 samples were looked at. 38 samples from the Maudach A 36 borehole also underwent preliminary analysis to roughly determine the pollen content, or subjected to counting a small number of pollen grains (Fig. 4, Fig. 5). The pollen sequences are mostly incomplete due to the variable tectonic subsidence of the URG and the fluvial dynamics which didn't allow a regular sedimentation.

The preliminary investigation of borehole P34 revealed at least parts of 5 interglacials and several glacial pollen sequences (Fig. 4, Fig. 5). At a depth of 13,6 m in the lower, fine-grained section of the OKL, the pollen assemblage (Lu-I-A in Fig. 5) had high values of *Corylus* (hazel) as well as *Picea* (spruce) and *Alnus* (alder), and low values of *Quercus* (oak), *Ulmus* (elm), *Carpinus* (hornbeam) and *Abies* (fir), which may indicate the early part of an interglacial sequence or a part of a temperate interstadial.

Another interglacial sequence was encountered in the OZH from 26.5 – 29.05 m. The lower part of this section (Lu-I-C) contains pollen from *Abies*, *Carpinus* and *Taxus* (yew), and massulae from *Azolla filiculoides* (large mosquito

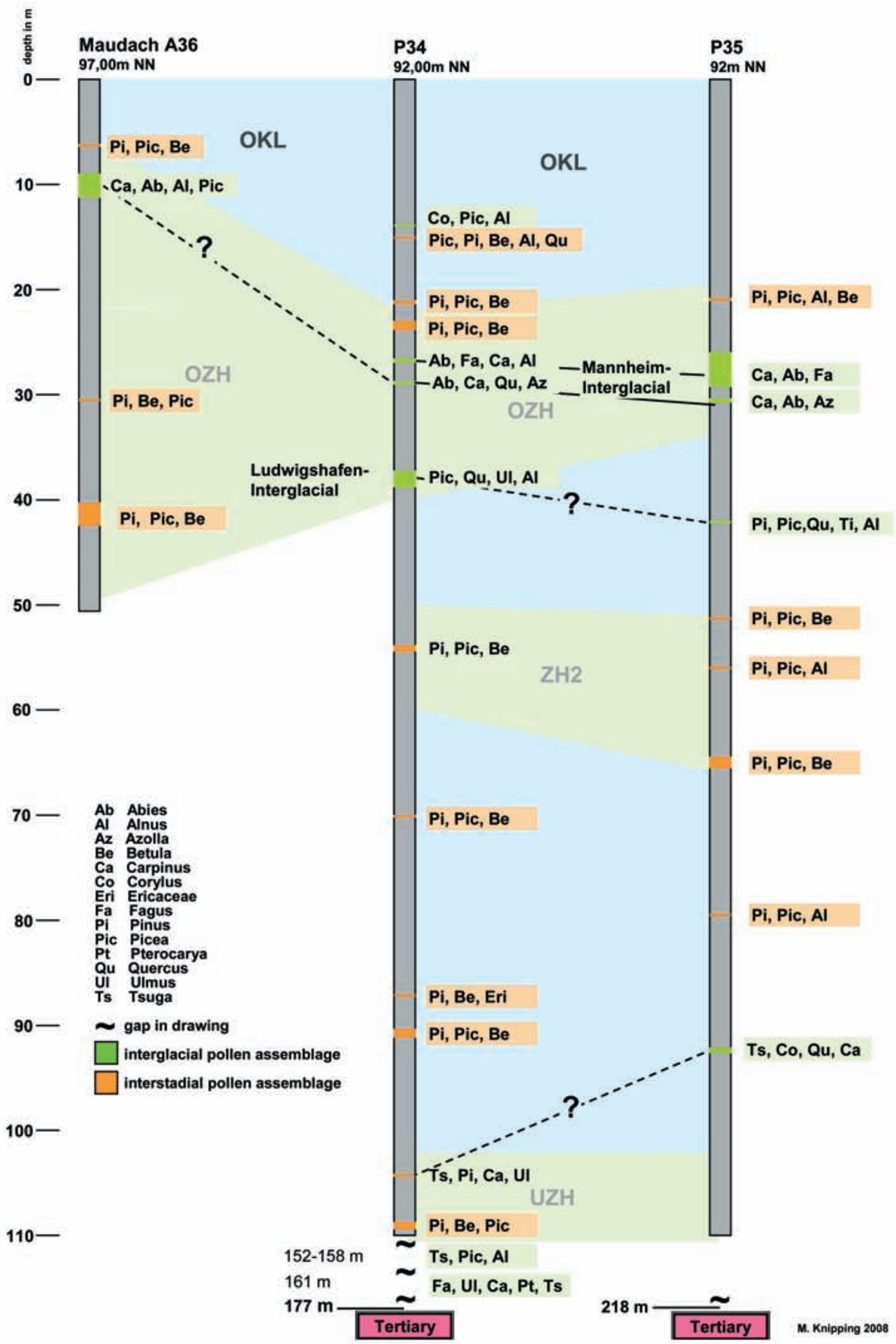

Fig. 4: Summary of the preliminary pollen analysis results from boreholes P34, P35 and Maudach A36.

Abb. 4: Übersicht der pollenanalytischen Voruntersuchungen der Bohrungen P34, P35 und Maudach A36.

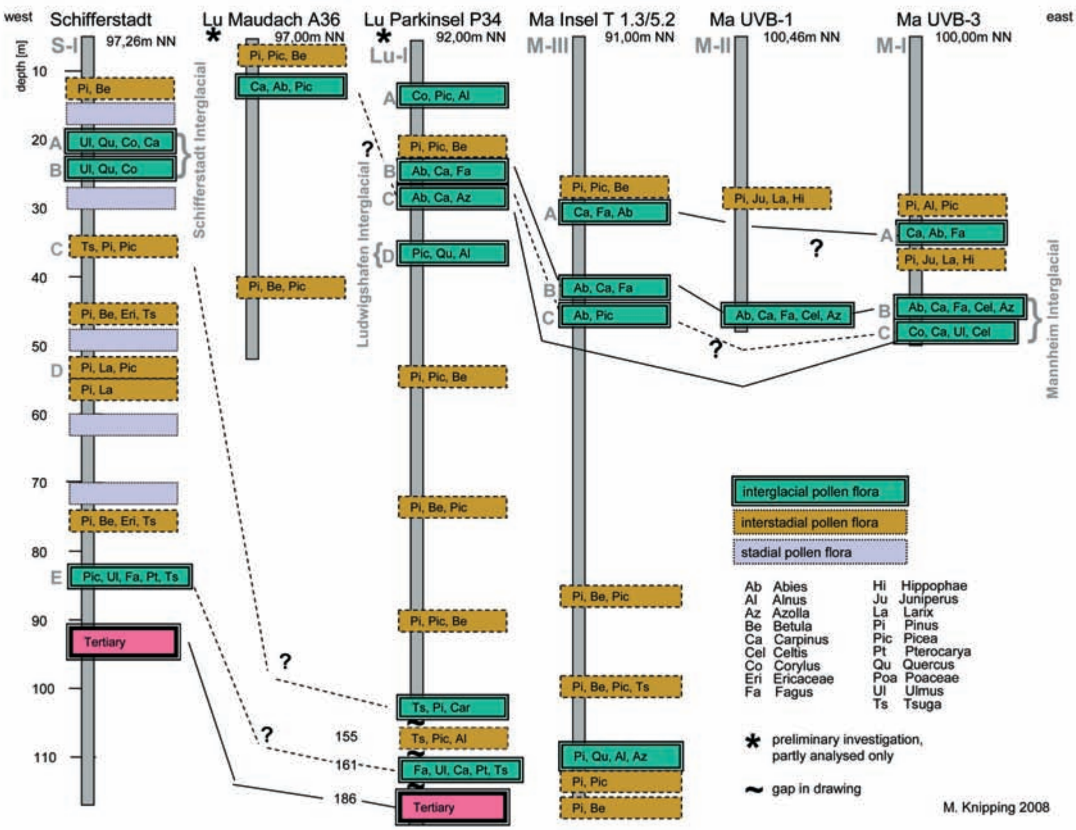

Fig. 5: Summary and preliminary correlation of the investigated pollen sections in the Schifferstadt/Ludwigshafen/Mannheim area.

Abb. 5: Übersicht und vorläufige Korrelation der untersuchten Pollenprofile im Raum Schifferstadt/Ludwigshafen/Mannheim.

fern), whilst the upper part (Lu-I-B) contains pollen from *Fagus* (beech). A further interglacial pollen assemblage (Lu-I-D, Ludwigshafen Interglacial) containing *Picea, Quercus, Alnus, Ulmus* and *Corylus* was present between 36.9 – 38.4 m.

Two samples from the UZH (103 m) contain several grains of *Tsuga* (hemlock) in a pollen assemblage dominated by *Pinus* (pine), together with *Picea*, *Carpinus* and *Ulmus*. Other spectra with *Tsuga*, *Picea*, *Alnus* and *Pinus* occur at a depth of 152.4 – 158.4 m. High concentrations of *Fagus* pollen alongside *Quercus, Ulmus, Carpinus, Pterocarya* (wingnut), *Ostrya* type (hop hornbeam) and *Tsuga*, were recovered at a depth of 161.45 m. A Tertiary pollen spectrum was identified in two separate samples at 186 and 201 m.

In the first analysis of borehole P35, which involved the zone down to a depth of 93 m, there were at least three interglacial sequences alongside several glacial pollen spectra (Fig. 4). An analogous interglacial sequence was found at a similar depth to that in borehole P34. In the lower part of this sequence (30.4 – 30.7 m) pollen from *Abies, Carpinus* and *Quercus* were identified, along with massulae from *Azolla*. In the upper part (26.2 – 29.0 m), *Fagus* pollen was also found. The decline in pollen from thermophilous taxa (from 26.5 m) and the marked increase in *Pinus* pollen appears to show the end of the interglacial. A pollen spectrum with *Pinus*, *Picea*, *Corylus*, *Quercus* and *Alnus* is also found at 42.1 m. Two interglacial pollen spectra including *Tsuga*, as well as *Corylus*, *Quercus* and *Carpinus* were identified in fine-grained horizons (91.1 – 92.45 m) below the UZH.

In the OZH at Maudach A36 a pollen sequence (9.0 – 11.2 m) shows interglacial conditions characterised by high amounts of *Carpinus* (up to 40 %) shifting to woodland richer in *Abies*, then in *Picea* and dominated at last by *Pinus* and *Betula*. Until now *Fagus* is absent, even though several samples have been analysed. Pollen of *Buxus* has values up to 5 % in the lower part of the interglacial.

3 Discussion

It should be stressed in advance that the following correlations are only tentative in character because they are based on preliminary analysis, and complete analysis of the samples still remains to be done. The pollen sequences recorded to date are often fragmentary and there are uncertainties when correlating these with other pollen sequences. Publications covering the boreholes from the Mannheim area (Knipping 2004, 2008) already include some of the results of the preliminary analysis of the P34 borehole, which provided an invaluable addition to and confirmation of the biostratigraphic classification of the penetrated sequences.

For the interglacial or temperate interstadial pollen spectrum at a depth of 13.6 m in the OKL in borehole P34, a Holocene or Eemian age can be rejected, but a correlation with either one of the Early Weichselian interstadials or an interglacial older than the Eemian is possible (Knipping 2008). No analogous pollen spectrum has so far been found in P35.

P34 contains pollen spectra (26.5 – 29.05 m) which are correlatable with a high degree of probability with the Middle Pleistocene Mannheim Interglacial (Knipping 2008). Borehole P35 (Fig. 4) also revealed pollen spectra at a similar depth which, because of the presence of *Carpinus*, *Abies* and *Azolla* in the lower part (30.4 - 30.7 m), and the additional occurrence of *Fagus* in the upper part of the interglacial (26.2 - 29.0 m), correlates with a high degree of probability with the interglacial in P34 (Lu-I-B + C) and therefore with the Mannheim Interglacial (Fig. 4, Fig. 5). According to the pollen spectra identified to date, the upper part of the interglacial is represented in P35 by a section with a thickness of 2.8 m, and is thus much thicker than in P34 where the thickness is only 0.3 m. The lower part of the interglacial has a similar thickness in both boreholes with a thickness of approx. 0.3 m.

Comparison with other Middle Pleistocene interglacials indicates that the most likely correlation for the Mannheim Interglacial is with the Rhume Interglacial (Müller 1986, 1992) and the Kärlich Interglacial (Urban 1983, Bittmann 1992). The interglacial section of Meikirch II (Welten 1982, 1988) was recently reinterpreted by Preusser et al. (2004), and the former “Eemian” is now correlated with MIS 7. There are some similarities with the Mannheim Interglacial, but *Celtis* which is present in the Mannheim Interglacial as well as the Kärlich Interglacial is not present at Meikirch.

The interglacial found in the OZH in P34 at 36.9 – 38.4 m (Lu-I-D) is primarily characterised according to the current degree of analysis by the absence of *Carpinus*, *Abies* and *Fagus*. There are some similarities to the pre-Rhume thermomere described by Müller (1992) and the interglacial found by Bludau (2001) at approx. 47 – 52 m in the Mannheim Ergo BK 3 borehole. Interglacial pollen spectra without *Carpinus*, *Abies* and *Fagus* were only found in two horizons at 42 m in borehole P35. It is not certain at this stage whether these correlate with Lu-I-D. Should this correlation be confirmed, then there is a very marked difference in the thickness of the sequence in P34 (1.5 m) and the 0.1 m thick sequence in P35.

Another cored borehole in the Ludwigshafen area (Maudach A36) was also included in this preliminary analysis (Fig. 1, Table 1). An interglacial with high proportions of *Carpinus* is reported in the OZH at a depth of 9 – 11.2 m. Based on the current status of the preliminary analysis, this cannot be correlated with the younger part of the Mannheim Interglacial because no *Fagus* has been found. It is possible that this interglacial correlates with the older part of the Mannheim Interglacial. If this is true, the Mannheim Interglacial represents two separate interglacials because the end of the interglacial appears to have been reached in Maudach A36 with the transition to *Pinus*-richer sections. The presence of a gastropod fauna in the same borehole at a depth of 23 – 28 m, which Wedel (2008) interprets as indicating the Cromerian Complex, could indicate a possible classification as Cromerian. Another consequence of a correlation between Maudach with the older part of the Mannheim Interglacial would be to make the correlation between the Mannheim Interglacial with the earlier "Eemian" at Meikirch (Preusser et al. 2004) very unlikely (see above), because *Carpinus* pollen is very rare in the two lower interglacials of Meikirch "Holstein 1" and "Holstein 2" (Welten 1982, 1988), but accounts for nearly 40 % in Maudach. The Upper Pleistocene position of the interglacial at Maudach at a depth of 9 – 11.2 m cannot, however, be excluded on the basis of the current status of the pollen analysis.

Interdisciplinary analysis in the northern part of the Upper Rhine Graben, which in addition to looking at the lithostratigraphy, also looks at "Upper Pleistocene" mammal remains, gastropods, wood remains and pollen, provided no reliable stratigraphic classification of the material (Koenigswald 1988). Dating of parts of the Upper Gravels (OKL) and the "Oberer Ton" (Upper Clay = OZH) to the last interglacial (Eemian) has, however, been favoured by some authors. However, the latest analysis by Knipping (2002, 2004, 2008) and Wedel (2008) has shown that the OZH in the Mannheim/Ludwigshafen area cannot be assigned to the Eemian but must be older. The analysis of gastropods from the "Upper Clay" in the Mannheim-Lindenhof borehole (Rähle 2005) gave a Middle Pleistocene, probably Cromerian age. The same samples contained analogous pollen spectra to those found in the Mannheim Interglacial (Knipping, unpublished). This, as well as the work of Engesser & Münzing (1991) in the Mannheim area support the palynological correlation of the OZH with the Cromerian Complex. Two boreholes of Mannheim (Knipping 2004, 2008) contained additional pollen from thermophilous taxa above the Mannheim Interglacial, including *Carpinus* and *Fagus* (Fig. 5). Because these are only single samples, the question still remains open of whether these can be correlated with interglacials younger than the Mannheim Interglacial. It does, however, support the correlation of the Mannheim Interglacial with the Cromerian Complex.

No Middle Pleistocene pollen spectra with *Pterocarya*, which could be correlated with the Holstein/*Pterocarya* Interglacial (Müller 1974, Grüger 1983, Drescher-Schneider 2000) have so far been identified in the boreholes in Mannheim, Schifferstadt or Ludwigshafen. The Schifferstadt Interglacial described in the Schifferstadt borehole (Knipping 2002), is also probably equivalent to the Ferdynandowian Interglacial (Janczyk-Kopikowa 1975), and has also not been identified so far in the two boreholes in Ludwigshafen.

Increased subsidence of sub-blocks during the Plio-Pleistocene in the northern Upper Rhine Graben around the Mannheim/Heidelberg area is not only indicated lithostratigraphically, but also by pollen analysis. According to the initial investigation, the P34 and P35 boreholes penetrated sediments down to a depth of 102 m in which at least 3 superposed interglacials have been partially identified (Knipping 2004, 2008). *Tsuga* occurs from approximately 103 m in P34 and 92 m in P35, which currently still indicates a Lower Pleistocene age. Notable in this context is the single identification of a *Tsuga* pollen grain in the lower part of the Mannheim Interglacial (UVB-3) (Fig. 5) (Knipping 2008). Indications that *Tsuga* could also be present in the Cromerian Complex are supported by the analysis conducted by Bludau (2001) in the Mannheim Ergo BK3 borehole. The author describes several isolated occurrences of *Tsuga* in an interglacial and discusses a possible Cromerian age. In addition, in the Schifferstadt

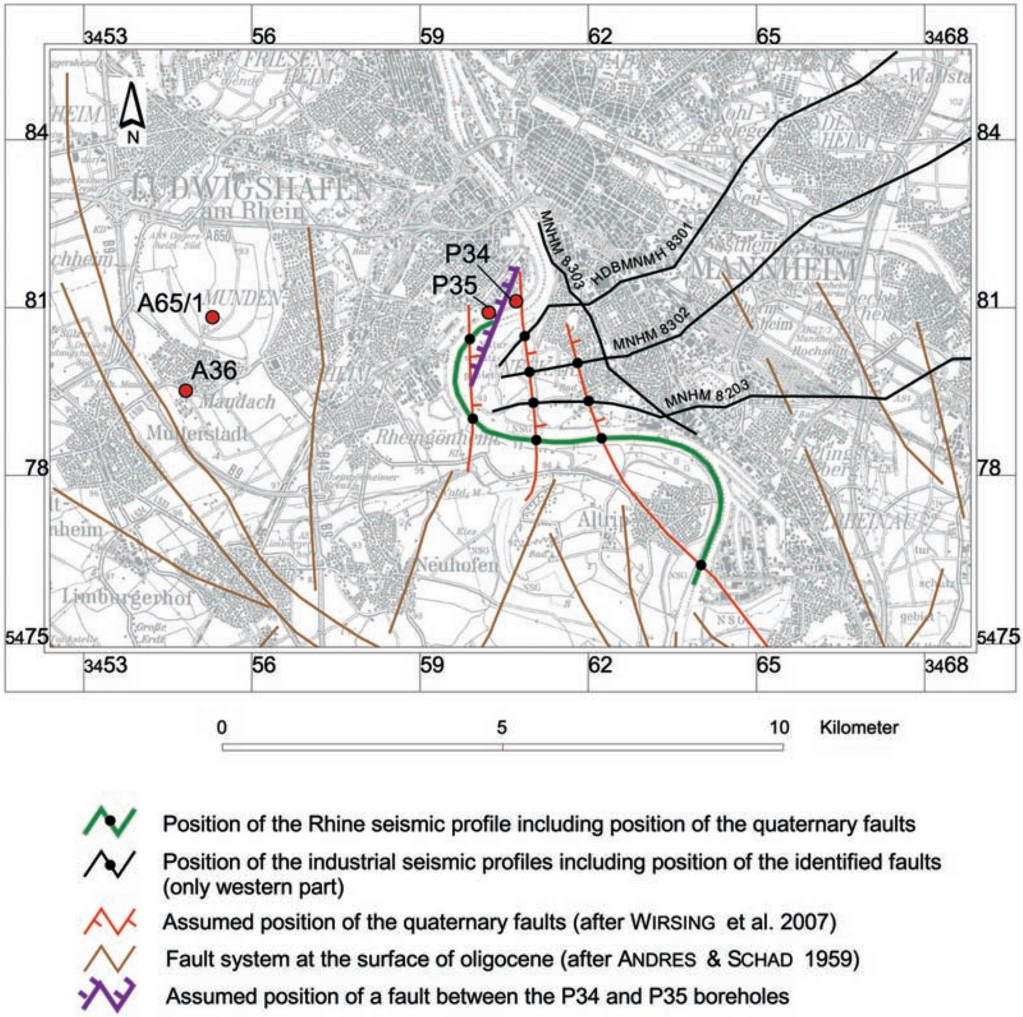

Fig. 6: Assumed position of a fault between the Ludwigshafen P34 and P35 boreholes, depicting the position of the Quaternary faults, interpreted on the basis of industrial seismic and river seismic profiles (after WIRSING et al. 2007).

Abb. 6: Vermuteter Verlauf der Störung zwischen den Bohrungen Ludwigshafen P34 und P35 mit Darstellung des Verlaufs quartärer Störungen, entwickelt aus industrieseismischen und flussseismischen Profilen (nach WIRSING et al. 2007).

borehole lying further to the west (KNIPPING 2002), which is also described as containing a Middle Pleistocene interglacial (Schifferstadt Interglacial), several occurrences of *Tsuga* have been confirmed at depths below 36 m. This section has therefore been preliminarily correlated with the Lower Pleistocene down to the Plio-Pleistocene boundary at approximately 91 m. The Middle-Lower Pleistocene boundary and Quaternary base deepen in these boreholes from west to east in the direction of the centre of the Heidelberg Basin. The Quaternary base in the Viernheim research borehole is at a depth of 224 m (HOSELMANN 2008).

Lower Pleistocene and Tertiary sediments from the northern Upper Rhine Graben have mainly been looked at in the Schifferstadt borehole. Various interglacial and glacial vegetation sequences were described here in the older sections (Knipping 2002). Lower Pleistocene sediments have so far only been recorded in the P34 borehole. The occurrence of *Tsuga* pollen, together with *Picea*, *Alnus* and *Pinus* at 152.4 – 158.4 m, points more to cool climatic conditions, but no detailed biostratigraphic subdivision is currently possible. Pollen spectra with high proportions of *Fagus,* in addition to *Tsuga*, *Pterocarya*, *Carpinus*, *Quercus* and *Picea,* occur at 160.45 – 161.45 m. Because of the common occurrence of *Fagus*, it can probably be classified as lying within the Tegelen Complex, probably Tegelen A (Zagwijn 1963). Tertiary pollen spectra at 186 and 201 m in P34, combined with heavy mineralogical and palaeomagnetic and rock-magnetic analysis, confirm the Plio-Pleistocene boundary at 177 m. No pollen analysis has yet been carried out on the Lower Pleistocene and Pliocene sections in borehole P35.

The new results of the analyses of borehole P35 (heavy minerals, carbonate content, lithofacies profile, gamma ray log) indicate that the Plio-Pleistocene boundary in borehole P35 is not at 183 m depth as implied by the first interpretation, but probably more likely at a depth of 218 m. Because the base of the Quaternary in the P34 borehole was confirmed at a depth of 177 m (Knipping 2008, Rolf et al. 2008), the Plio-Pleistocene boundary in borehole P35 probably lies approximately 42 m deeper. The large difference in depth within a distance of only 500 m cannot be explained by fluvial dynamics alone. It is more likely that the two boreholes are separated by a fault, and that borehole P34 lies on the upthrown and P35 on the downthrown side of the fault. The river seismic survey shot on the Rhine, and the interpretation of industrial seismic sections, indicate the presence of young faults in the Ludwigshafen/Mannheim area (Bertrand et al. 2006, Haimberger et al. 2005, Wirsing et al. 2007). These easterly dipping faults indicate the en-echelon faulted subsidence of the Quaternary base from west to east in the direction of the centre of the Heidelberg Basin (Fig. 6). Throws of up to 10 m at the base of seismic horizon 2 (OZH and Middle Sandy-Gravely Series) are interpreted from the seismic sections. In general, the faults identified in the Ludwigshafen/Altrip area can be linked to three NNW-SSE running, easterly dipping antithetic downthrown faults (Wirsing et al. 2007). Because the drilling location of borehole P34 lies approximately 500 m ENE of borehole P35, it must be assumed that a sub-block lying further to the west has subsided more strongly (P35), an anomaly when compared to the regional situation. It is possible that a previously unidentified WNW-ESE running transverse fault separates this sub-block from the easterly lying sub-block on which borehole P35 was drilled. Indications of young tectonic movements in the northern Upper Rhine Graben are documented in numerous recent publications (Peters et al. 2005, Peters & van Balen 2007a, 2007b, Weidenfeller & Kärcher 2008). Interestingly, the Quaternary faults are very closely related to faults which cut the Tertiary sediments and the base of the Tertiary (Andres & Schad 1959, Derer et al. 2005).

Because the upper 122 m of the P34 and P35 boreholes can be very well correlated in terms of thickness, as well as sedimentary facies and gamma logs, it is assumed that tectonism was particularly active prior to the start of sedimentation of the Lower Intermediate Horizon (UZH), and that it then weakened considerably. Because the OZH is assigned to the Cromerian Complex on the basis of current findings (Knipping 2008, Rähle 2005, Wedel 2008), and because the UZH is also assigned to the transition zone between the Lower and Middle Pleistocene, the phase of tectonism giving rise to the approximately 42 m throw is considered to have taken place during the latest Pliocene and Lower Pleistocene. It seems clear that this period was characterised by more rapid subsidence of the Heidelberg Basin, and thus the Ludwigshafen-Mannheim area as well, and that this rapid subsidence was compensated for by high rates of sedimentation.

4 Conclusions

Fluctuating fluvial dynamics over very short distances leave behind strongly differentiated sequences in the geological record which can only be approximately interpreted with the information gained from several cores. The differences in the nature of the sediments between the P34 and P35 boreholes highlights that the interpretation of the climatic and fluvial history of an area on the basis of the analysis of a few boreholes becomes very difficult because the sediments are not only affected by fluvial dynamics, but also by small-scale tectonics. The complex fault pattern in the northern Upper Rhine Graben is partially responsible for the preservation and character of the sediments. Unlike major cycles which can still be recognised and correlated across several boreholes, closer analysis reveals the presence of frequent gaps which make interpretation more difficult. Sedimentation is often controlled by young tectonics where small-scale fault block movements can result in the deposition of very different sequences of sediments, as recorded in the cores. The clear characterisation and stratigraphic identification based on several independent methods, and on pollen analysis in particular, provides the information required to make reliable interpretations of the sedimentation history influenced by palaeoclimatic fluctuations and tectonic movements. The differences identified by comparing the two boreholes P34 and P35, which are only 500 m apart, emphasise that the large-scale correlation of boreholes separated from one another by several tens of kilometres, will only succeed when the sediments in the cores are analysed using analogous methods and can be stratigraphically classified.

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The Pliocene and Pleistocene fluvial evolution in the northern Upper Rhine Graben based on results of the research borehole at Viernheim (Hessen, Germany)

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Abstract: The research borehole drilled in 2006 by the Hessian Agency for the Environment and Geology (HLUG) north of Viernheim (Hessisches Ried) reached a total depth of 350 m, and penetrated high resolution fluviatile and limnic-fluviatile sediments (0 to 225 m) of Pleistocene age, and partially highly pedogenically overprinted limnic-fluviatile sands, clays and silts of Pliocene age (225 to 350 m). The Pliocene sediments tend to be sourced locally. The sediments repeatedly show sourcing from the Odenwald which is characterised by a high percentage of green hornblende in the heavy mineral fraction. As part of the Heidelberg Basin research programme, one of the main purposes of this borehole was to analyse the Pleistocene "Normal Facies" of the northern Upper Rhine Graben, i.e. a sedimentary sequence subject to minimum disturbance, largely unaffected during the Pleistocene by material sourced from the graben margins or smaller tributaries.

The Pleistocene sedimentary sequence consists of three units: a thin horizon with reworked Pliocene material is overlain by ten cycles each beginning erosively with gravely sandy sediments and ending with silty-argillaceous to in part peat-like sediments. Internal cycles can also be identified, amongst other features. A characteristic aspect is the green-grey, strongly calcareous, micaceous and well sorted, fine to medium sands of the Rhine. These are dominated by the Rhine Group (garnet, epidote, green hornblende and alterite) in the heavy mineral fraction. These sediments are classified as the "Rhenish Facies". The upper Pleistocene sedimentary sequences at the top of the Viernheim research borehole are dominated by several fining-upward and in part coarsening-upward sequences. The deposits in this part of the well are dominated by gravel deposited by the Neckar. The heavy mineral distribution of the sand fraction reveals, however, that there was mixing with Rhenish sediments.

Weichselian to Holocene aeolian sands form the topmost part of the well section. The stratigraphic classification of the Pleistocene sedimentary sequences is still uncertain in parts. The Pliocene-Pleistocene boundary is placed at 225 m because of the characteristic change in facies. Due to lithostratigraphic correlations with sediments within the Lower Rhine Embayment, a larger unconformity at the depth of 225 m must be accepted. Research carried out in the area around the well indicates that the youngest fine-clastic section penetrated by the well between 39.76 and 58.55 m is of Cromerian age.

[Die pliozäne und pleistozäne fluviatile Entwicklung im nördlichen Oberrheingraben unter besonderer Berücksichtigung der Forschungsbohrung Viernheim (Hessen, Deutschland)]

Kurzfassung: Die 2006 durch das Hessische Landesamt für Umwelt und Geologie (HLUG) abgeteufte Forschungsbohrung nördlich von Viernheim (Hessisches Ried) hat mit einer Endteufe von 350 m hoch aufgelöst fluviatile und limnisch-fluviatile Sedimente (0 bis 225 m) des Pleistozäns und zum Teil stark pedogen überprägte limnisch-fluviatile Sande, Tone und Schluffe des Pliozäns (225 bis 350 m) durchteuft. Die Liefergebiete der pliozänen Sedimente sind eher regional geprägt. Die Sedimente zeigen wiederholt Schüttungen aus dem Odenwald, die durch einen hohen Anteil grüner Hornblende in der Schwermineralfraktion gekennzeichnet sind. Als Teil des Forschungsprogramms „Heidelberger Becken" zielte diese Bohrung insbesondere

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im Pleistozän auf die „Normalfazies“ des nördlichen Oberrheingrabens ab, das heißt: auf eine möglichst ungestörte Sedimentabfolge, die im Pleistozän Schüttungen von den Grabenrändern oder kleineren Zuflüssen weitestgehend ausschließt.
Die pleistozäne Sedimentabfolge besteht aus drei Einheiten: über einem geringmächtigen Horizont mit aufgearbeitetem pliozänen Material folgen zehn Zyklen, die erosiv mit kiesig sandigen Sedimenten einsetzen und mit schluffig-tonigen bis zum Teil torfigen Ablagerungen abschließen. Mitunter sind interne Zyklen zu erkennen. Charakteristisch sind grünlich-graue stark carbonatische, glimmerführende und gut sortierte Fein- bis Mittelsande des Rheins. In diesen dominiert die Rhein-Gruppe (Granat, Epidot, grüne Hornblende und Alterit) in der Schwermineralfraktion. Diese Sedimente werden als „Rheinische Fazies“ bezeichnet.
In der hangenden letzten pleistozänen Sedimentabfolge der Forschungsbohrung Viernheim bestimmen mehrere fining-upward und zum Teil coarsening-upward Sequenzen das Sedimentationsgeschehen. Die Ablagerungen dieses Profilabschnitts sind Kies dominiert, der vom Neckar geschüttet worden ist. Die Schwermineralverteilung der Sandfraktion zeigt aber an, dass es zu einer Vermischung mit rheinischen Sedimenten gekommen ist. Weichsel- bis holozänzeitliche Flugsande schließen das Profil ab.
Die stratigraphische Einstufung der pleistozänen Sedimentabfolge ist in Teilen noch unsicher. Die Pliozän-Pleistozängrenze wird auf Grund des charakteristischen Fazieswechsels auf 225 m gelegt. Eine überregionale Korrelation mit Sedimenten der Niederrheinischen Bucht spricht für eine Diskordanz mit größerer zeitlicher Lücke an der Plio-Pleistozängrenze. Untersuchungen im Umfeld der Bohrung sprechen für cromerzeitliches Alter des jüngsten feinklastischen Abschnitts der Bohrung zwischen 39,76 und 58,55 m.

Keywords: Quaternary, Pleistocene, Pliocene, Cromerian Complex, fluvial sediments, heavy minerals, Carbonate, Upper Rhine Graben, Germany

1 Introduction

The north-eastern part of the Upper Rhine Graben (URG) is known as the “Hessisches Ried” (Fig. 1). This area has become an important research area for Quaternary graben development in recent years. According to Van Gijssel (2006), the URG is a non-glaciated type region for mid Central European large and medium sized upland basins.
The historical landscape development in the late and post-glacial period in the northern URG was recently studied by Bos et al. (2008), Dambeck (2005), Dambeck & Bos (2002), Dambeck & Thiemeyer (2002) as well as Erkens et al. (2009). The geometry of the Quaternary sediment body was investigated using high resolution reflection seismic by Haimberger et al. (2005) and Wirsing et al. (2007). The interaction between tectonics, and fluviatile and erosive processes, particularly along the western graben margin, was investigated by Peters & Van Balen (2007a, b) as well as Peters et al. (2005). The sedimentological structure of the Pleistocene sedimentary fill in the northern Upper Rhine Graben has, however, not been looked at systematically in recent times. This was one of the reasons why the Geological Survey of Hessen (Hessisches Landesamt für Umwelt und Geologie (HLUG)) drilled several research boreholes in the Hessisches Ried in recent years. In addition to scientific aspects concerning the sedimentology, sedimentary petrography, vegetation history, palaeontology and tectonic development during the Pleistocene and Upper Pliocene, the investigation was also interested in applied geological aspects, which require a thorough understanding of the structure of the graben fill for their clarification. The focus of this aspect of the investigation was on hydrogeology, resource geology and geothermy.
The boreholes were designed to reveal the geometry of the Pleistocene sedimentary body in more detail, and to specify each of the facies in the area of investigation. The thickness of Quaternary sedimentary fill increases from the western to the eastern graben margin. There is also an increase in thickness from north to south-east in the direction of the Heidelberg Basin (Fig. 2). At the eastern graben margin of the Hessisches Ried, the fluviatile or limnic-

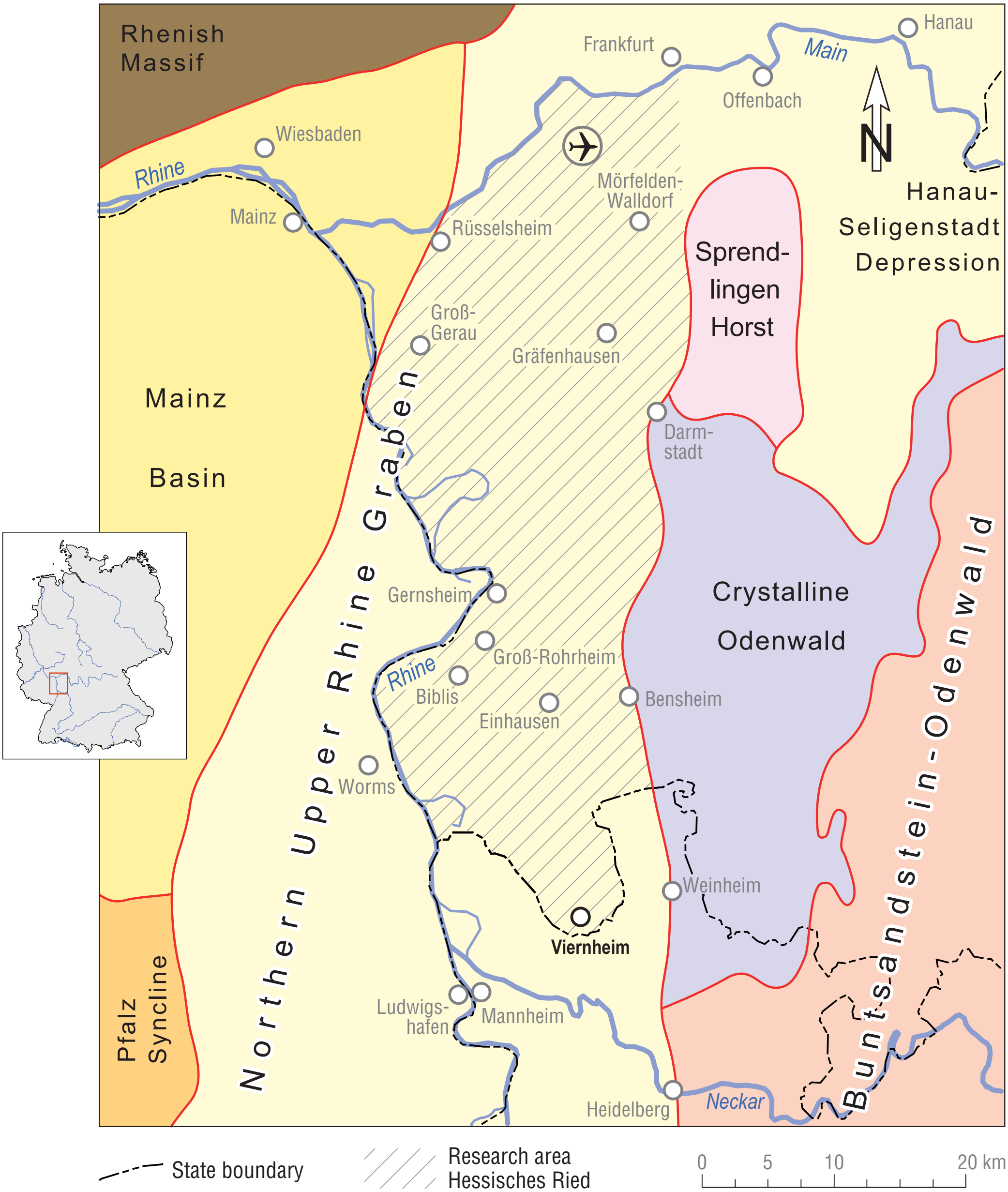


Fig. 1: Location map with the geological structural zones and the area of investigation "Hessisches Ried".

Abb. 1: Übersichtskarte mit den geologischen Strukturräumen und dem Untersuchungsgebiet „Hessisches Ried".

fluviatile deposits repeatedly contain interbeds of redeposited sediments of hard rocks lying on higher ground further east, i.e., from the Odenwald or the Sprendlingen Horst. This hard rock, consisting of Palaeozoic crystalline rocks and sedimentary rocks of Rotliegend age (Sprendlingen Horst) and Buntsandstein, was intensively weathered during the Mesozoic and Tertiary. The resulting unconsolidated rock was easily eroded and redeposited during the Pleistocene periglacial periods. Directly along the graben margin in particular, there are also very high proportions of redeposited sediments derived from these source areas. The 111 m deep C/04 B1 borehole drilled south of Gräfenhausen north-west of Darmstadt (R 3472203 – H 5531111 based on the Gauss-Krüger coordinates of German topographic maps), clearly shows an almost 20 m thick sequence of redeposited sediments aligned east-west in this part of the northern URG, forming part of the Quaternary sedimentary sequence with a total thickness of 83.58 m. These redeposited sediments can be traced for approx. 5 km from the graben margin in the northern URG. The Pleistocene fluviatile graben fill itself consists in the area of investigation of alternating fluviatile sands and gravels mixed up in various proportions, as well as silts, clays and peat. This sequence is the "Normal Facies" of the northern URG.

In the north part of the Hessisches Ried, the Rhenish sediments interfinger with the fluviatile sediments deposited by the Main river. Several hundred boreholes were geologically analysed and recorded by HLUG between 2003 and 2004 during the planning work for the Deutsche Bahn's ICE high speed rail track from Frankfurt/Main airport (Rhine-Main district) to Mannheim (Rhine/Neckar zone). This revealed the presence of fluviatile sediments, laid down by the Main all the way up to the area to the north of Gräfenhausen (borehole 2.3/41 drilled along the planned ICE track: R 3472332 – H 5533832). On the other hand, indisputable Rhenish sediments were also found as far north as the southern edge of Frankfurt airport. For instance, the borehole drilled close to the west runway (BK 1200; R 3465891 – H 5542863) revealed Pleistocene, calcareous sediments of the Upper Rhine Graben beneath the Lower Pleistocene Untermain-Hauptterrassen Formation (Hoselmann 2007a). A research borehole drilled to the north of Mörfelden (R 3468725 – H 5538979) also penetrated Main and Rhine sediments. Limnic-fluviatile and fluviatile sediments of Pliocene age were penetrated below the base of the Quaternary at 64.5 m below ground level. The "Walldorf Horst" postulated by Anderle & Golwer (1980) with thin Quaternary sediments lying on unconsolidated Miocene sediment is therefore non-existent.

In the eastern part of the Hessisches Ried, the fluviatile sediments of the northern URG are overlain by a few metres of Weichselian aeolian sands, partially drifted to form dunes. The thickness of the aeolian sands can even exceed 30 metres in places, for instance, at the western edge of the town of Darmstadt. This means that the aeolian sands may also have been redeposited and incorporated in the normal facies of the Pleistocene graben fill. Sedimentation in the western part of the Hessisches Ried ended with Holocene fluviatile sediments laid down by various meander generations of the Rhine (Dambeck 2005 amongst others).

The aim of the Viernheim research borehole was to derive a standard section for the "Normal Facies" of the graben fill in the northern URG, and to provide detailed descriptions of these sediments with regard to the sedimentology, sedimentary petrography, palaeobotany and palaeontology. It was also the intention to date these sediments by physical dating methods such as OSL, IR-RF, TIMS-^{230}Th/U and Burial Age Dating (Dehnert & Schlüchter 2008; Preusser et al. 2008; Geyh 2008) and to provide information on sedimentation rates where possible. The form of subsidence in this region means that large parts of the section can be expected to be preserved in superposition.

The work on the Viernheim research borehole is closely related to other research activities in the Heidelberg Basin (Ellwanger et al. 2005). The first results of this work have already been published, particularly on the Ludwigshafen-

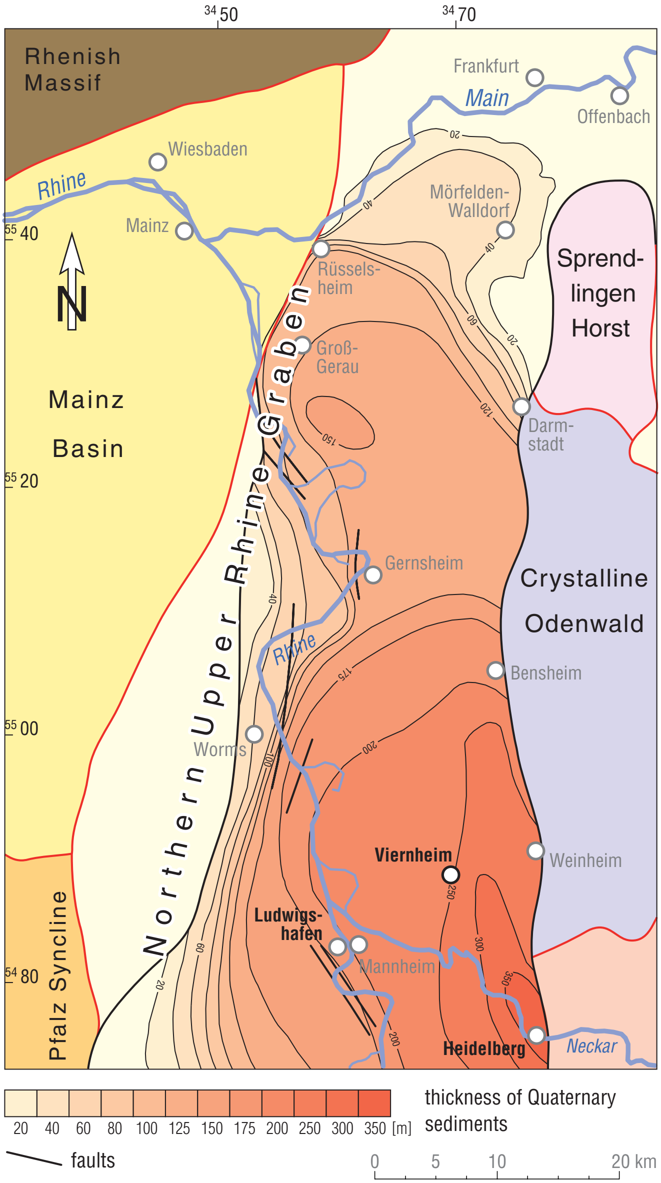


Fig. 2: Thicknesses of the Quaternary sediments in the northern URG; redrawn from BARTZ (1974), HAIMBERGER et al. (2005) as well as a great deal of new information from this work. The thickness of the Quaternary sediments increases from north to south as well as from west to east. The Heidelberg Basin begins in the Hessisches Ried south of Gernsheim. Around Heidelberg, a more strongly subsided subbasin revealing approx. 400 m of Quaternary sediments is documented.

Abb. 2: Mächtigkeitsverteilung quartärer Sedimente im nördlichen URG; umgezeichnet nach BARTZ (1974), HAIMBERGER et al. (2005) sowie mit verschiedenen Aktualisierungen aus dieser Arbeit. Generell ist eine Zunahme quartärer Sedimente von Norden nach Süden sowie Westen nach Osten zu erkennen. Das Heidelberger Becken beginnt im Hessischen Ried südlich von Gernsheim und bildet bei Heidelberg ein noch stärker abgesenktes Teilbecken mit einer maximalen Quartärmächtigkeit von rund 400 m.

Parkinsel borehole. Of particular interest here is the work on sedimentary petrography (Hagedorn 2004; Hagedorn & Boenigk 2008), the fluviatile development during the Middle and Upper Pleistocene (Weidenfeller & Kärcher 2008), palaeomagnetics (Rolf et al. 2008), palaeobotany (Knipping 2004, 2008; Weidenfeller & Knipping 2008) and tectonics (Ellwanger et al. 2008).

2 Geological description of the Viernheim research borehole

2.1 Viernheim research borehole

The Viernheim research borehole lies almost 2 km to the north of Viernheim in the Hessisches State Forest, and specifically on the Buchnerschneise (R 3469080 – H 5492215; height of the borehole drilling location: 96.95 m asl; cf. point 5 in Fig. 10). The borehole was drilled by the drilling contractor Daldrup & Söhne from January to June 2006. Down to the total depth (TD) of 350 m, cores were cut in liners with an internal diameter of 10 cm. The sediments penetrated by the borehole were ram cored to a depth of 40,5 m. The wireline rotary coring method was then used to cut the next cores down to a depth of 64 m. The cored section from 64 m to 228 m was again cut by ram coring. The wireline rotary coring method was again used from 228 m down to 350 m TD. Despite some technical problems during coring, the quality of the cores is very good with core recovery of approx. 97 %. The cores were sliced in halves: one half for scientific analysis and one half to be archived in the core store.

The borehole can be subdivided into two chronostratigraphic sections. From 350 m TD up to a depth of 225 m, the section largely consists of fine-clastic sediments assigned to the Pliocene on the basis of their lithological character, composition, pedogenic overprinting, and supra-regional correlation. The section from 225 – 221.21 m is a transition zone between Pliocene and the Pleistocene. The overlying sequence largely consists of Pleistocene fluviatile sediments.

The discussion in the following dispenses with detailed core descriptions. This material can be requested from the author by e-mail, along with photo documentation and analysis data.

2.2 Subdivision of the sedimentological record

A strongly simplified description of the borehole section is shown in Figure 3. The Pliocene sequence can be subdivided as follows:

Unit	Depth in m below ground level	Description summary	Special aspects
10	225-228	Fine-clastic cycle with numerous calcareous clusters; slightly oxidised in the lower part, repeatedly strongly reduced at top	Without strong pedogenic overprint
9b	228-228,6	Strongly humic from here on, lignite in part	
9a	228.6-238.5	Fine-clastic sediments, similar to unit 7, dominantly reduced	Without strong pedogenic overprint
8	238.5-250.45	With fining-upward sequence starting with gravely sand (together with unit 9), repeated fine gravely horizons, silty in the upper part; reduced in part	With local sediment source probably from the Odenwald; section damaged during drilling

Unit	Depth in m below ground level	Description summary	Special aspects
7	250.45-261	Fine-clastic sediments, strongly spotted: reduced and oxidised, calcareous in clusters (similar to unit 1a, 3 and 5)	Pedogenic overprint = "Plinthosol"
6	261-270.44	Sand-dominated unit with a silt horizon at 268-268.85 m; largely reduced, also oxidised zones	Local sedimentary source, probably from the Odenwald
5	270.44-315.85	Compact unit similar to 1a, 3 and 7; silts and clays, with repeated discordant interbeds of sand, also calcareous in clusters, predominantly strongly oxidised and some reduced zones	Strong pedogenic overprint = "Plinthosol"; Unit discordantly overlain by 6
4	315.85-318.55	Sand deposits, upper part reduced, silty in part	Local sediment source, probably from the Odenwald
3	318.55-323.1	Similar to unit 1a, 3, 5 and 7, compact/ homogenous	Only weak pedogenic overprint
2	323.1-330.62	Sand-dominated unit, layered in part, at 329-330 m with fine-gravely clasts; humus in parts with redeposited lignite	Local sediment source, probably from the Odenwald
1b	330.62-333.4	Fine clastic, humus-banded, with sandy horizons, with a lot of fine sand towards the base, at the top similar to 1a	
1a	333.4-350	Fine-clastic sediments, strongly spotted: reduced and oxidised, calcareous in clusters	Strong pedogenic overprinting = "Plinthosol"

The Pliocene sediments are marked by a higher bedding density than the overlying sediments. The Pliocene sediments are followed discordantly by a short section which mainly consists of reworked Pliocene sediments. This zone is given a preliminary chronostratigraphic classification as Plio-Pleistocene – this section consists of:

Unit	Depth in m below ground level	Description summary	Special features
11	221.21-225	Fining-upward sequence of fine sand to silt, clayey, strong humic concentrations in parts in the upper section	Transition zone with numerous reworked Pliocene sediments

This sequence is overlain by Pleistocene sediments. Up to 39.76 m below ground level, this sequence is divided into 10 cycles (I-X) which have similar internal structures that vary in thickness and with respect to other parameters. Generally the cycles are repeated sequences of fining-upward suites which begin discordantly with sandy-gravely sediments. Every sequence

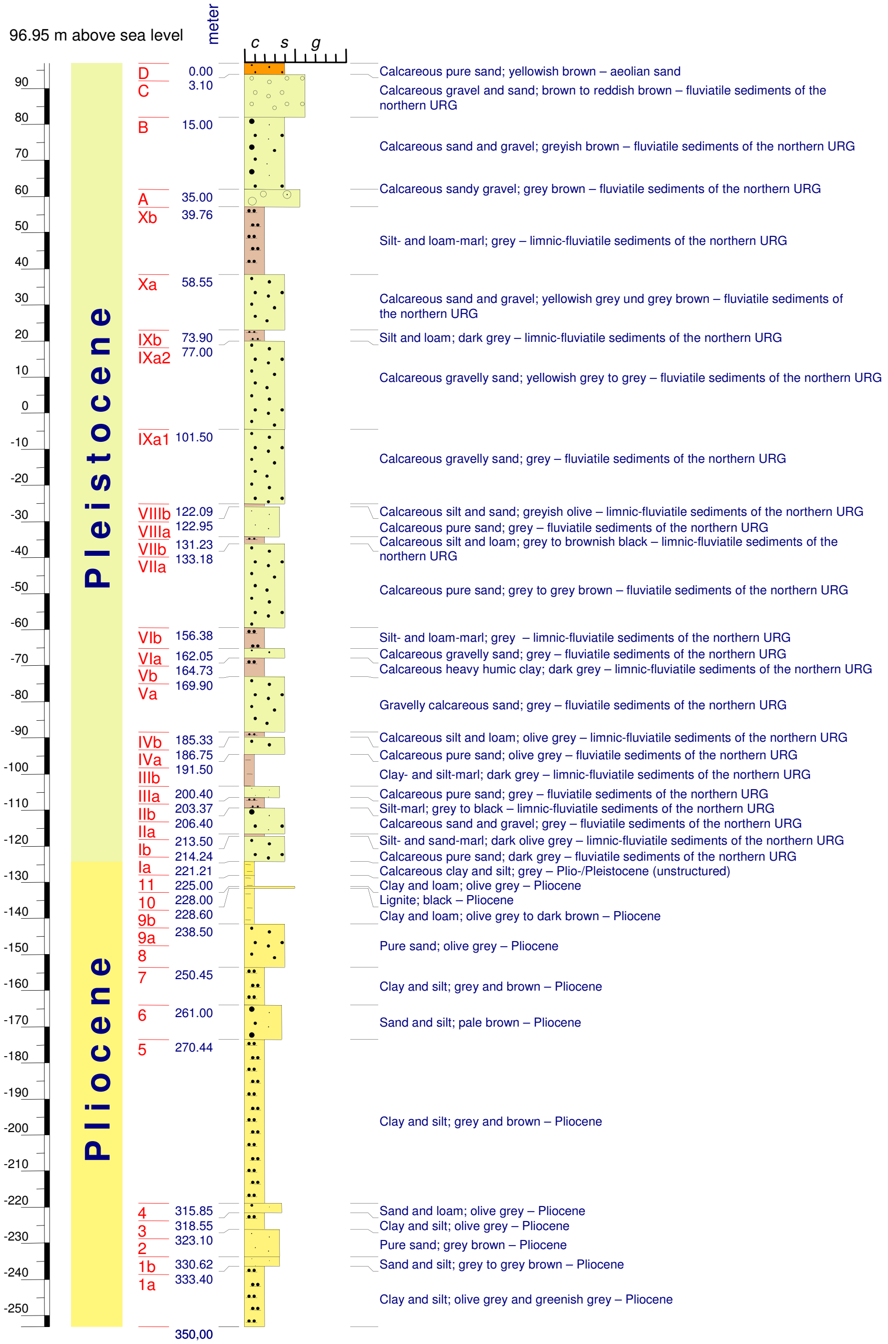


Fig. 3: Schematic geological section of the Viernheim research borehole showing a summary of the sedimentological units.

Abb. 3: Schematisiertes geologisches Profil der Forschungsbohrung Viernheim mit den zusammengefassten sedimentologischen Einheiten.

Table 1: Summary of some characteristic sediments occurring in the area drilled by the Viernheim research borehole.

Tab. 1: Zusammenfassung einiger charakteristischer Sedimente, die im Gebiet der Forschungsbohrung Viernheim auftreten.

	characteristic features
fluvial gravels and cobbles of the Rhine	Quartz, quartzite, crystalline rock, lydite, radiolarite
fluvial gravels and cobbles of the Neckar	Muschelkalk and Late Jurassic limestone, Buntsandstein sandstone, Keuper sandstone
Rhenish Facies	well to very well sorted fine up to medium grained sands, carbonate rich, greenish grey, light mica

ends with fine-clastic silts and clays. Other sequences can be identified within these cycles. The description repeatedly mentions sediments in "Rhenish Facies" (Table 1). This is a well to very well sorted grey to greenish-grey fine to medium grained sand. The carbonate content can exceed 20 % in part.

A characteristic feature is the distinctive presence of mica. The light mica flakes can have diameters up to several millimetres.

This part of the well section has the following geological setup (cf. Figure 3):

Section	Depth in m below ground level	Description summary	Special features
Xb	39.76-58.55	Dominantly fine-clastic with sandy intercalations, partially in Rhenish Facies, at 49 and 53.5 m strongly humic, five partial sequences in total, humic clays and peat in the upper section	51.9-52.5 m in typical Rhenish Facies
Xa	58.55-73.9	The cycle begins with sand and some gravel, coarsening upwards, from 67-69 m reddish because of the stronger Neckar influence, then fluctuating fine gravel portions	Concretionary in part due to calcareous content
IXb	73.9-77	Fine-clastic sediments, reduced at the bottom, then humic up to 75 m, followed by strong humic peat and finally by silt	70-80 m, 87.2-88.2 and 101,8-103 m in typical Rhenish Facies
IXa2	77-101.5	Marked change in colour from grey to more reddish colours up to 98 m Coarsening-upward sequence, from 88.2 m again sediments in Rhenish Facies, becoming more fine-grained upwards	Notable colour change IXa2 to IXa1. IXa2 with strong influence from Neckar sediments?
IXa1	101.5-122.09	VIIIb is discordantly overlain by sandy zone with subordinate interbedded gravely horizons	

Section	Depth in m below ground level	Description summary	Special features
VIIIb	122.09-122.95	Thin fine sandy silts	With calcareous concretions and geodes
VIIIa	122.95-131.23	VIIb is erosively overlain by sands with gravel grading into fine to medium-sized sands towards the top, 123-123.5 m oxidised, high concentrations of light mica in part	124.5-126.5 m in typical Rhenish Facies
VIIb	131.23-133.18	Fine clastic, reduced, more humic towards the top with sandy intercalations, oxidised in part	
VIIa	133.18-156.38	VIb is erosively overlain by gravely sands, becoming coarser upwards as a coarsening-upward sequence, then dominant sand with gravely horizons, sand at the top	133.8-134 m in typical Rhenish Facies
VIb	156.38-162.05	Fine clastic sediments with gravely interbeds at 161.1-161.45 m, silt and clay weakly reduced with oxidation zones	Characteristic banding
VIa	162.05-164.73	Vb is discordantly overlain by next fining-upward sequence starting with gravely sands	
Vb	164.73-169.9	Fine clastic zone reduced at the bottom and more humic towards the top, from 168.2 m reduced, in part oxidised, then humic again	Gravels largely from the Neckar
Va	169.9-185.33	IVb is erosively overlain by coarse sands, gravely in part, very gravely at 182.5 m, fluctuating gravel concentrations in this section	169.9-172.5 m in typical Rhenish Facies. Pedogenic overprint in part
IVb	185.33-186.75	Silts and clays, partially reduced	Similar to IIIb
IVa	186.75-191.5	IIIb is discordantly overlain by coarser sands, grading into typical sands of the Rhenish Facies	
IIIb	191.5-200.4	Silts and clays, strongly humic in part, light grey to dark greenish-grey (reduced)	
IIIa	200.4-203.37	IIb is discordantly overlain by well sorted, micaceous sands without gravely horizons	With typical Rhenish Facies, fining upward sequence overall

Section	Depth in m below ground level	Description summary	Special features
IIb	203.37-206.4	Fine-clastic sediments, humic in part, also reduced	
IIa	206.4-213.5	Ib is discordantly overlain by sandy gravel grading up into sand dominated sediments, with abundant mica in parts	Dominant limestones in the gravel fraction
Ib	213.5-214.24	Mainly silts, reduced	
Ia	214.24-221.21	Fining-upward sequence with gravely sands and sands	First sediments in Rhenish Facies

This part of the section is overlain by a more coarse clastic carbonate unit more strongly influenced by Neckar sediments (A to C), top of the sequence formed by Weichselian to Holocene aeolian sands (D).

Unit	Depth in m below ground level	Description summary	Special features
D	0-3.1	Markedly coarse, pedogenically overprinted aeolian sand	0-1 m core loss
C	3.1-15	Gravely sands and gravels with fining-upward and coarsening-upward sequences, Rhenish portion strongly reduced	Neckar gravels
B	15-35	Four fining-upward sequences, inhomogeneous, 27-32 m gravel	With Rhenish Facies in the fine grained parts, Neckar gravels
A	35-39.76	Xb is discordantly overlain by gravely sands to gravels in three fining-upward sequences	With Rhenish Facies in the fine grained parts, Neckar gravel

The cycles I-X reveal fluviatile and limnic-fluviatile sediments which were mainly deposited by the Rhine. Mixing with Neckar sediments occurs in the gravely parts. Units A-C are, however, much more strongly dominated by gravel, and the influence of Rhenish sedimentation reduces upwards.

Gravel analysis was carried out at various depths to determine the provenance of the gravel (Table 2).

There are basically no significant changes in the gravel content. The values are similar to those for the area of the Neckar alluvial fans described by e.g. LÖSCHER (1988). The fractions analysed are dominated by Keuper limestones and sandstones transported by the Neckar, as well as red sandstones from Buntsandstein areas. The interesting finding is that the limestones in the lowest sample in particular are partially dissolved. In addition to the Neckar pebbles, there is also mixing with a local component from the Odenwald. This is revealed by the relatively high proportion of red sandstones derived from the Buntsandstein, as well as crystalline pebbles. These are less well rounded, which indicates shorter transport distances.

Table 2: Summary of the gravel analysis at various depths in the Viernheim research borehole. The figures are percentages and add up to 100 % in total. 200 to 500 pieces of gravel were counted in the fraction higher than 5 mm.

Tab. 2: Zusammengefasste Schotteranalysen aus verschiedenen Teufenbereichen der Forschungsbohrung Viernheim. Die Werte geben Prozent an und summieren sich insgesamt auf 100 %. Gezählt wurden zwischen 200 und 500 Kiese der Fraktion größer 5 mm.

Layer	Depth [m]	quartz	crystalline	red sandstone (Buntsandstein)	limestone (Late Jurassic)	limestone (Muschelkalk)	lydite	sandstone (e.g. Keuper)	miscellaneous (chert, radiolarite, phyllite, claystone, quartzite, and marl)
C	5.3-5.75	20.5	22.5	8.5	17.0	17.2	1.6	6.7	6.0
B	31.7-31.8	16.2	11.4	3.1	18.3	29.3	2.6	4.1	15.1
IXa2	99-99.5	6.5	15.9	19.4	26.4	13.9	2.0	9.0	7.0
VIIa	148.2-148.5	26.6	10.5	12.2	16.7	20.7	1.1	9.6	2.5
VIb	161.3-161.4	12.9	11.3	3.5	39.5	13.2	6.4	7.7	5.5

The limestones are well to very well rounded because of their longer transport distances and lower hardness. The portions of up to 26.6 % quartz, and lydite occurring as an accessory component, indicate mixing with Rhine pebbles. These were transported long distances from either the Black Forest or the Alps.

3 Results

3.1 Heavy Mineral Analysis

Various systematic investigations of the heavy mineral composition of Pliocene and Pleistocene sediments in the Upper Rhine Graben have been undertaken previously (e.g. Van Andel 1950; Maus in Bartz 1982; Boenigk 1987; Hagedorn 2004; Hagedorn & Boenigk 2008). Heavy mineral analysis is an important instrument for characterising fluviatile Pliocene and Pleistocene fine sands from the Rhine system as part of work conducted in the middle Rhine area, the Lower Rhine Embayment and the Netherlands. The composition of the heavy mineral distribution provides information on the source of the sediments as well as the weathering of the sediments.

171 samples from the Viernheim research borehole were analysed for their heavy mineral content. The main analytical method was that of Boenigk (1983). Sodium polywolframate ($Na_6(H_2W_{12}O_{40})*H_2O$) with a density of 2.85 g/cm^3 was used as the heavy liquid to separate the heavy from the light fraction in a centrifuge. The samples were boiled with concentrated hydrochloric acid prior to centrifuging to remove iron and manganese hydroxide crusts which would complicate the identification. The disadvantage of this method is the dissolution of carbonate, apatite and parts of monazite and olivine (Boenigk 1983). This was deemed acceptable because of the benefit of being able to make comparisons with our own and other previous analyses.

Generally, the sediments in the borehole from a depth of 350 to 225 m are dominated by the stable heavy mineral group (Fig. 4). These are mainly zircon, but also tourmaline and rutile.

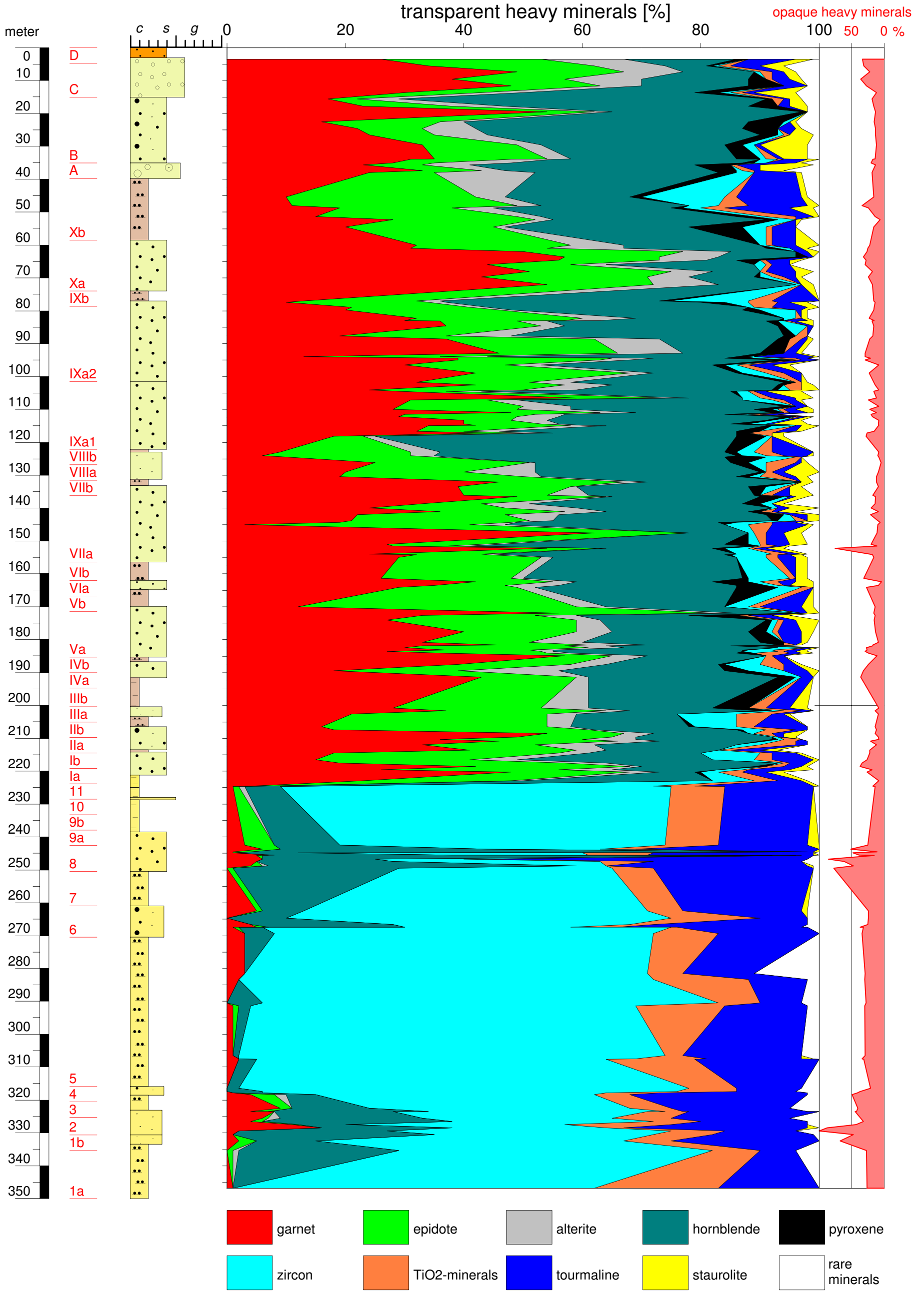


Fig. 4: Heavy mineral diagram on 171 sand samples from the Viernheim research borehole; hornblende includes green and subordinate brown hornblende; the TiO_2-group includes rutile, brookite and anatase; the rare minerals include andalusite, sillimanite, disthene, titanite, monazite and spinel.

Abb. 4: Schwermineraldiagramm an 171 Sandproben der Forschungsbohrung Viernheim; Hornblende beinhaltet grüne und untergeordnet braune Hornblende; die TiO_2-Gruppe schließt Rutil, Brookit und Anatas ein; die seltenen Minerale fassen Andalusit, Sillimanit, Disthen, Titanit, Monazit und Spinell zusammen.

Subordinately also occur heavy minerals of the Rhine Group (garnet, green hornblende and epidote) (cf. also Fig. 5). However, some samples have very high percentages of dark green hornblende (up to 86 %).

The composition of the heavy mineral spectrum changes significantly above sample 222,9-222,8 m: zircon, the TiO_2-group and tourmaline become insignificant. These are replaced by garnet, epidote and green hornblende which determine the composition of the heavy minerals in the sand fraction, although the distribution overall remains relatively homogenous. This is emphasised even more when the heavy minerals are divided into separate groups (Fig. 5). The Rhine Group dominates with proportions between 60 and 80 %. Instable minerals have sometimes undergone strong alteration or are strongly dissolved. Garnet shows some evidence of corrosion, and green hornblende has been strongly altered in parts. Accessory minerals include the volcanic heavy minerals pyroxene and brown hornblende.

Boiling with concentrated HCl leads to the dissolution of some heavy minerals such as carbonate and apatite. A test run with 16 samples studied at the effect of the concentrated HCl treatment on the heavy mineral distribution. Figure 6 shows the distribution of selected samples with and without HCl treatment. Generally, the heavy mineral distribution remains the same with or without treatment. The differences lie within the range of statistical error. However, there is a significant rise in opaque heavy minerals (no HCl boiling), that is explained by the iron and manganese hydroxide encrustations on some grains which can therefore not be identified in transmitted light under a polarised microscope. Apatite now occurs in proportions up to 8 %, however, only in samples between 163.55 and 5.5 m. In general, counting during heavy mineral analysis becomes much more difficult, and some grains can only be identified after a lot of work. The difference for the sediments in the Upper Rhine Graben is, however, not as significant because of the presence of carbonate-rich sands which have not been subject to any very intensive weathering processes after sedimentation (cf. Chapter 3.2). Heavy mineral analysis without boiling with HCl is very difficult in the non-calcareous Pleistocene terrace deposits with no overburden to protect them from weathering, which are characterised by strong iron and manganese hydroxide deposits, and are frequent in the Middle Rhine and Lower Rhine areas. This can give rise to erroneous results. Decisions to change the methodology should therefore be looked at very critically because changing the methodology would considerably restrict direct comparison with most of the old analysis data collected in the Rhine area.

3.2 Analysis of the Carbonate Content

The carbonate content was analysed in 136 sand samples from the Viernheim research borehole. The samples were initially ground up in a mortar before being ground down to ca. 100 µ in a ball mill. The carbonate content was determined using the method described by Scheibler (DIN ISO 10693), which involved two to three measurements. The results were used to derive an average number. Total carbonate content was determined in each case. The carbonate in sediments from the Upper Rhine Graben primarily consists of calcite ($CaCO_3$), and to a lesser extent also dolomite ($CaMg(CO_3)_2$).

The analysed sediments are almost all calcareous above the boundary at 225 m. Concentrations fluctuate significantly between 0.96 and 37.17 % (Fig. 7). The sediments in the lower sequences are almost completely non-calcareous. A notable finding is that the carbonate concentration in the Viernheim research borehole fluctuates very strongly in general. A similar carbonate distribution picture was also shown in sediments from the borehole drilled less than 1 km to the south down to a TD of 110 m to investigate the groundwater (STW Viernheim; R 3469366 – H 5491377; point 4 in Fig. 10). The carbonate concentration in 26 samples ranges from 0,02 to 26.85 %. The highest carbonate values are found in the fine clastic sediments (fine sands) predominantly in the

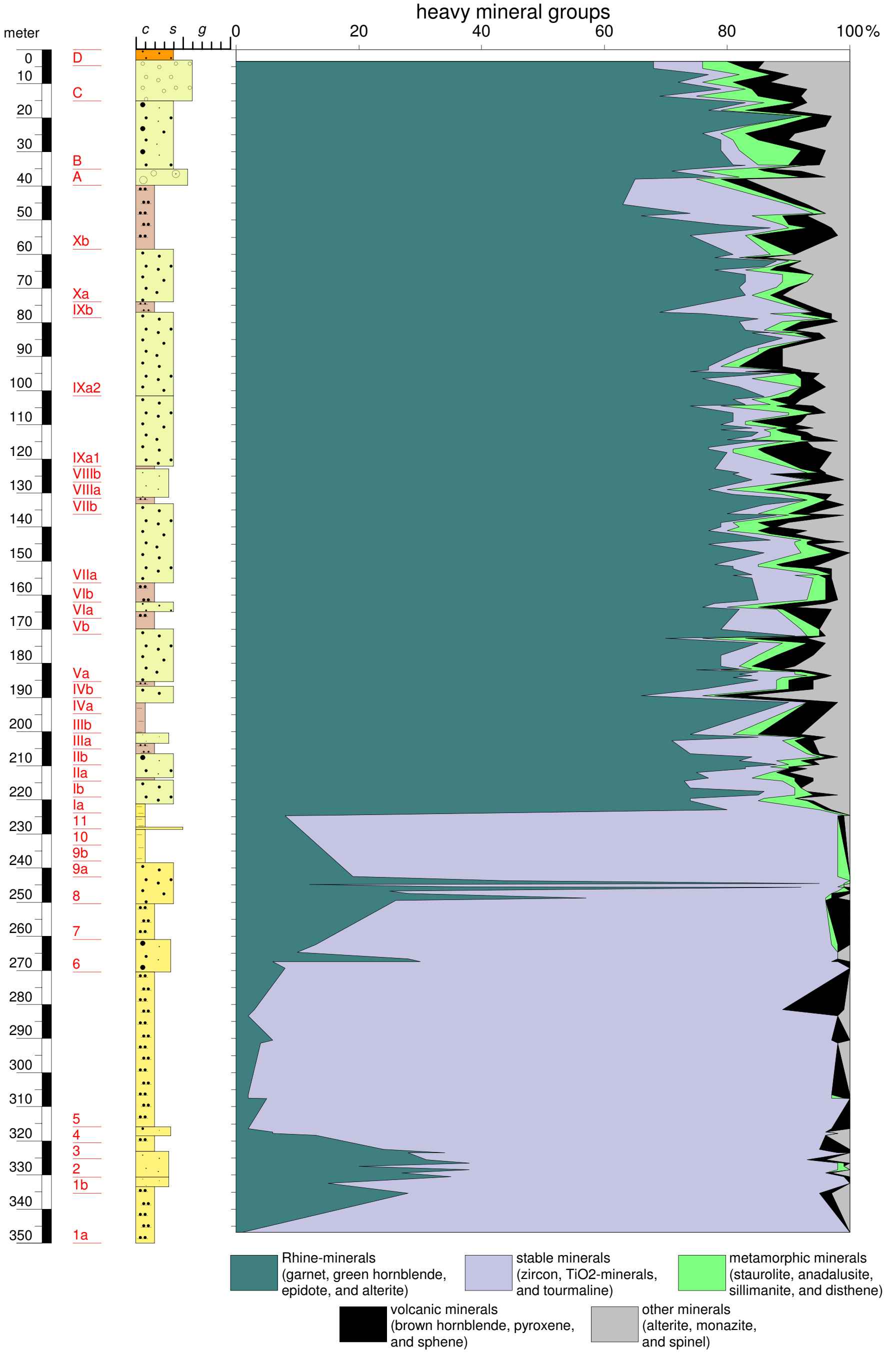


Fig. 5: Heavy mineral distribution divided into heavy mineral groups (after VAN ANDEL 1950 and VINKEN 1959), used for provenance analysis.

Abb. 5: Verteilung der Schwerminerale nach Schwermineralgruppen (nach VAN ANDEL 1950 und VINKEN 1959), die zur Liefergebietsanalyse verwendet wurden.

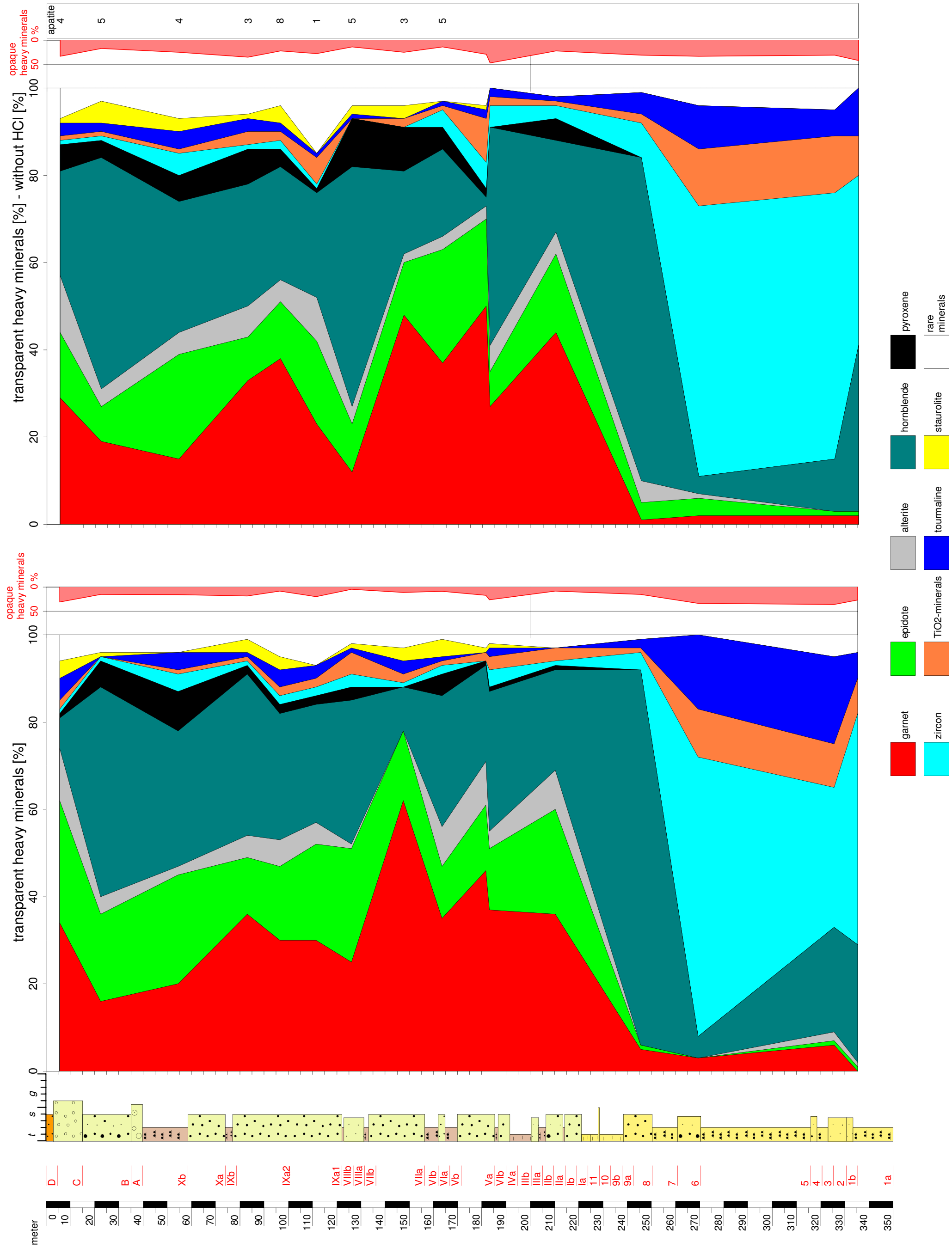


Fig. 6: Heavy mineral distribution in 16 selected samples from the Viernheim research borehole with and without HCl treatment. Apatite was counted separately in the samples prepared without boiling in HCl.

Abb. 6: Schwermineralverteilung von 16 ausgewählten Proben der Forschungsbohrung Viernheim mit und ohne Behandlung durch HCl. Bei der Probenaufbereitung ohne Kochen mit HCL wurden Apatite separat mitgezählt.

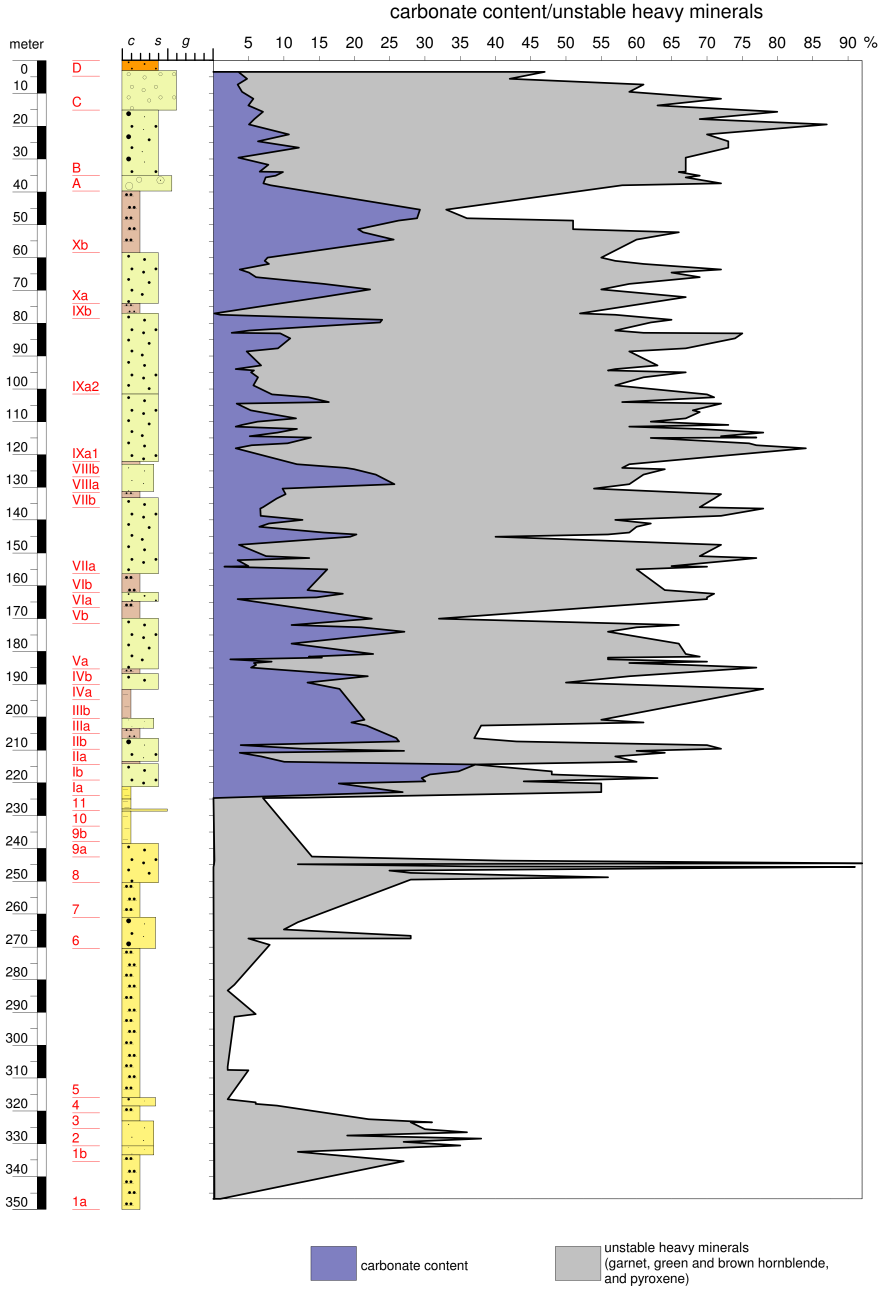


Fig. 7: Carbonate distribution from 136 sand samples from the Viernheim research borehole. The carbonate content is shown in relation to the group of unstable heavy minerals which weather easily in post-sedimentary environments.

Abb. 7: Carbonatverteilung von 136 Sandproben der Forschungsbohrung Viernheim. Der Carbonatgehalt wurde in Bezug zur Gruppe der instabilen Schwerminerale gesetzt, die postsedimentär leicht verwittern.

Rhenish Facies, as in the Viernheim research borehole. A similar picture is shown by another research borehole (C/00-BK01), lying between Biblis and Groß-Rohrheim (Fig. 1), approx. 18 km north-west of the Viernheim research borehole (R 3460250 – H 5508325). The Quaternary base lies almost 100 m below ground level. The carbonate concentrations in the 42 samples fluctuate between 1.39 and 22.71 %. They are therefore lower in general than the boreholes further to the south. However, the C/00-BK01 research borehole does not have the silty and clayey beds with fine sand intercalations which usually contain the calcareous sediments. Future work should investigate whether the distribution pattern of the carbonate concentrations can be correlated between boreholes.

4 Discussion

Subdivision of the Viernheim research borehole

The Viernheim research borehole can be divided into four sections (cf. Chapter 2). The zone from 350 to 225 m contains clay-rich, densely layered limnic-fluviatile deposits laid down on a floodplain. Some of these deposits have been subjected to strong post-sedimentary pedogenic overprinting giving rise to soils similar to plinthosols. These soils were formed by stagnant water or under the influence of groundwater, and have gley and pseudo-gley characteristics. Rust and bleach spots are typical of plinthosols. They are formed under humid-tropical climatic conditions. The fine clastic sediments contain calcareous clusters at some places and repeated intercalations of sandy deposits. Sections 8 to 9 (Fig. 3) comprise a fining-upward sequence topped by an organic sediment (lignite). The sands have partly high proportions of green hornblende indicating a local sedimentary source from the Odenwald situated to the east (Fig. 8). The extreme dominance of such an unstable mineral group (up to 86 %) must indicate the local provenance of the mineral because it would otherwise have become much more intensively mixed with extremely stable heavy minerals. Amphiboles formed by magmatic crystallisation or by metasomatic processes are typical for the crystalline Odenwald geology. In the other cases, the heavy mineral spectrum is characterised by high percentages of stable minerals such as the dominant zircons, but also tourmaline and the TiO_2-group. The Black Forest and the Vosges are interpreted as the sources of the subordinate proportions of garnet and epidote (Hagedorn & Boenigk 2008). Sections 1 to 10 (Fig. 3) of the well section are classified as Pliocene.

The next section (Section 11) is a transition zone which follows discordantly from 225 to 221.21 m and is interpreted as a reworked horizon. This section contains deposits derived from the underlying sediments which have been significantly reworked. In terms of heavy minerals, it contains a rather localised stable spectrum as well as a typical Pleistocene spectrum dominated by the Rhine Group. This section is preliminarily classified as Pliocene to Pleistocene.

The zone from 221.21 to 39.76 m in the Viernheim research borehole is made up of ten basically repeated suites (I-X) which begin autocyclically and discordantly with gravely sands and end with clayey sediments or peat. The thickness of each cycle fluctuates between 6.17 m (IV) and 48.19 m (IX). Additional partial sequences were identified in each cycle. The sediments (I-X) are almost exclusively medium to strongly calcareous. A typical feature is the repeated occurrence of very well sorted sands of the "Rhenish Facies" (cf. Chapter 2.2). These were formed by fluviatile flood sediments from the Rhine. The whole section in the well contains sediments dominated by the Rhenish Facies, with a gravel fraction which includes pebbles from the Neckar, and subordinately local components with crystalline pebbles from the Odenwald and red sandstones from the Buntsandstein. However, high percentages of quartz and the presence of lydite also show that the gravel fraction contains material sourced from areas to the south of the Neckar (Tab. 1 and 2).

The fluviatile part of the section is topped from 39.76 to 3.1 m by highly gravely sands and

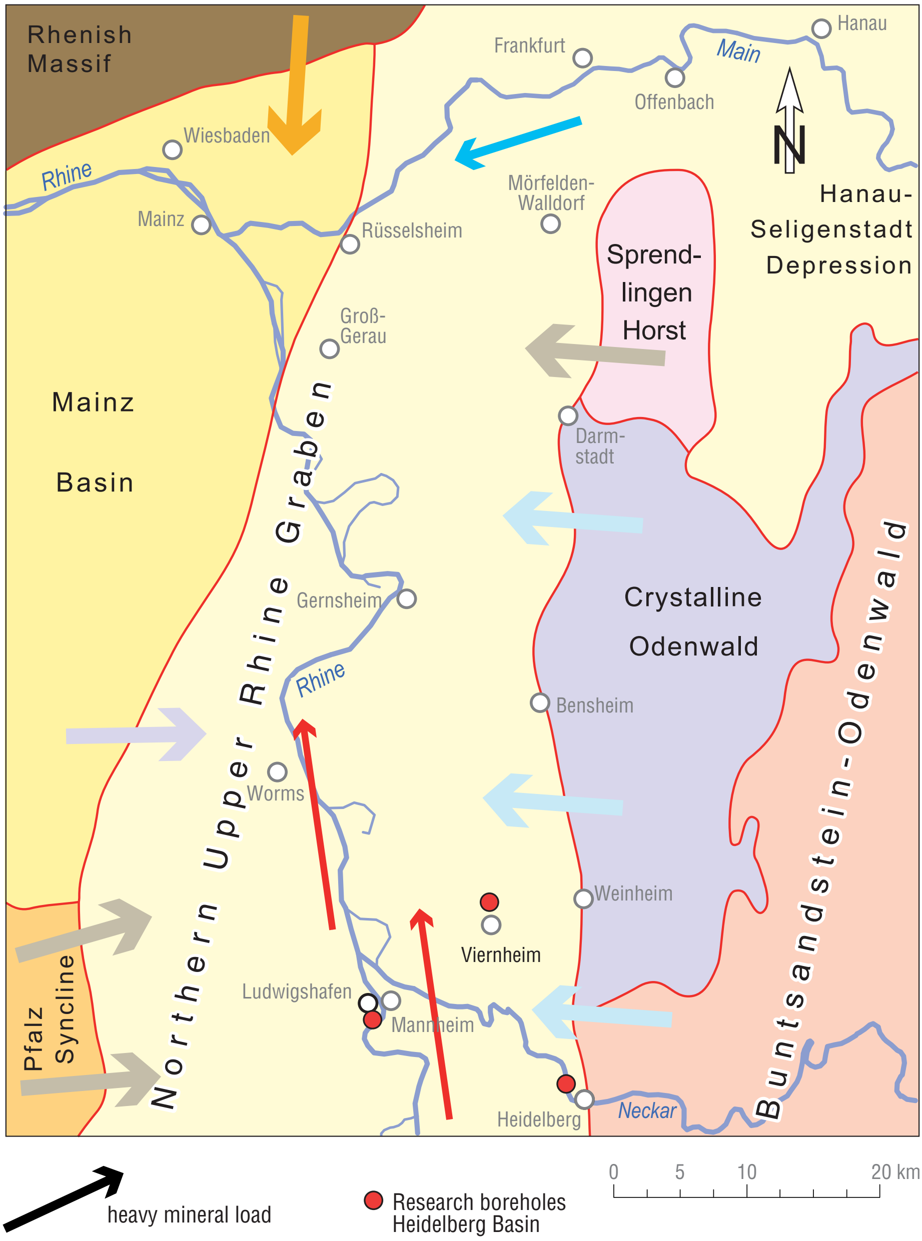


Fig. 8: Heavy mineral deposits during the Pliocene in the northern Upper Rhine Graben. Dominated by locally reworked sediments with stable heavy minerals and subordinate unstable heavy minerals derived from the Black Forest and the Vosges. Repeated local deposition from the graben margins which dominantly supply green hornblende in the eastern part of the northern URG.

Abb. 8: Schwermineralschüttungen während des Pliozäns im nördlichen Oberrheingraben. Dominant sind lokal aufgearbeitete Sedimente mit stabilen Schwermineralen und untergeordnet instabilen Schwermineralen, die aus dem Schwarzwald und Vogesen stammen. Wiederholt kommt es zu lokalen Schüttungen von den Grabenrändern, die im östlichen Teil des nördlichen URG dominant grüne Hornblende liefern.

gravels mainly laid down by the Neckar. The dominance of the Rhine Group in the heavy mineral fractions in the sands, however, indicates mixing with Rhenish sediments around Viernheim. This is also indicated by the quartz constituents and lydite in the gravel fraction (Tab. 2). This section is also marked by dominant fining-upward and subordinately coarsening-upward sequences. The top of the section from 3.1 m to the ground surface is formed by Weichselian to Holocene aeolian sands.

The unequivocal identification of the Rhine signal in the heavy mineral fraction of the sands can be deduced from the proportions of heavy minerals in the sediments. Unlike the Pleistocene Neckar sediments which only contain around 0.04 % heavy minerals, the Rhine sediments contain approx. 0.5 % heavy minerals. This means that the fluviatile Rhenish sediments have around 10 times more heavy minerals than the Neckar sediments (Fig. 9). Hagedorn (2004) reports similar findings. The change in provenance in sample 222.8 m show a strongly alpidic dominated heavy mineral spectrum, indicating the connection of the Rhine to the Alpine drainage system. The general homogenous structure of the heavy mineral distribution (Fig. 4 and 5) in the Pleistocene shows that lateral sources of sediment in the Viernheim area are almost completely absent. This locality is therefore different to that of the Ludwigshafen-Parkinsel borehole, for instance, which is marked by the periodic deposition of local sediments from the western graben margin (Hagedorn & Boenigk 2008).

This confirms the assumption by Hagedorn & Boenigk (2008), that the Rhine tended to flow in the eastern part of the northern URG during the Pleistocene. Subordinate proportions of volcanic heavy minerals (pyroxene and brown hornblende) are probably not associated with the initiation of Middle Pleistocene East Eifel volcanism prior to approx. 700 ka (Bogaard & Schmincke 1990). In principle, the Neckar could also be the source for the pyroxenes as well as the brown hornblendes, although a strong decrease in the pyroxenes is observed towards its confluence with the Rhine as a result of dissolution and dilution by tributaries (Van Andel 1950).

The importance of heavy mineral analysis for provenance analysis in the northern Upper Rhine Graben is highlighted by a comparison of the unstable heavy minerals (garnet, green and brown hornblende, and pyroxene) with the carbonate content (Fig. 7). The post-sedimentary weathering of sediments with a pedogenic overprint initially gives rise to a decrease in and relocation of the carbonate content. If the section has also undergone pedogenic overprinting, which was not obvious in the section, this would also have led to a decrease in the concentration of unstable heavy minerals. However, this is not the case in the Viernheim research borehole because zones with lower carbonate contents for instance have raised levels of unstable heavy minerals. No correlation is shown between low carbonate contents and low concentrations of unstable heavy minerals. This in turn means that the Pleistocene sediments have almost preserved their original heavy mineral association and are therefore ideal for provenance analysis. Some of the samples show signs of dissolution and traces of corrosion.

Stratigraphy

The lithostratigraphic subdivision of the Viernheim research borehole is proving difficult at the current state of the investigation because of the general absence of reliable data. The initial correlations can only be undertaken on the basis of analogies with other boreholes in the area, in the Lower Rhine Embayment (LRE), and in The Netherlands (detailed investigations in the Dutch/German border by e.g. Donders et al. 2007; Kemna & Westerhoff 2007; Westerhoff et al. 2008). The most distinct lithological changes in the borehole are at 225 m, and after the thin reworked horizon at 221.21 m. The change at 225 m is considered to be the boundary between the Pliocene and the Pleistocene. The Plio-Pleistocene boundary at 2.58 Ma is used in the sense of Bowen & Gibbard (2007), Gibbard & Cohen (2008), Litt

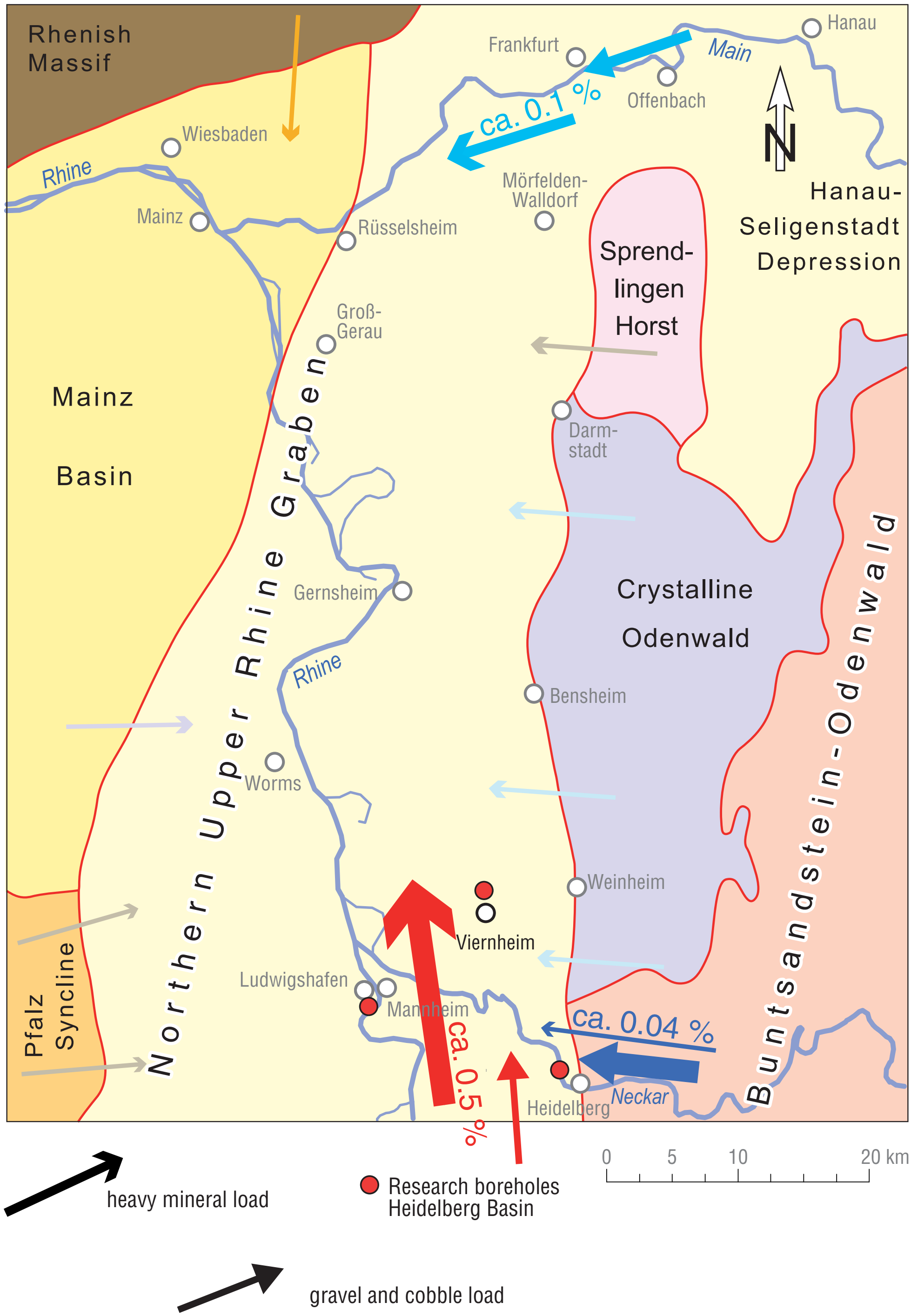


Fig. 9: Heavy mineral and gravel deposition during the Pleistocene in the northern Upper Rhine Graben.

Abb. 9: Schwermineral- und Kiesschüttungen während des Pleistozäns im nördlichen Oberrheingraben.

(2007), and Preusser (2008) and coincide with the palaeomagnetic Gauss/Matuyama boundary. The deposition of Rhine Group alpine heavy minerals in the URG already is of Late Pliocene age (Hagedorn & Boenigk 2008; Preusser 2008). Investigations in the LRE confirm this: a first shift from a stable heavy mineral spectra to unstable spectra of alpine type was detected in the Kieseloolite Formation (Kemna 2005, 2008 a, b). The Öbel beds (Latest Pliocene) also contain unstable heavy mineral spectra (Boenigk & Frechen 2006; Donders et al.2007; Kemna & Westerhoff 2007). In some parts of the LRE the Öbel beds cover the Reuver Clay s.s. and thus define the top of the Pliocene sedimentation. In the Viernheim research borehole, no typical alpine heavy mineral spectra can be found below a depth of 225 m. Consequently, these sediments are correlated with the Pliocene. A larger unconformity at this depth must be accepted. There is no doubt that a marked change in sedimentation took place at that time. At the present stage of the investigation a further stratigraphic subdivision of these Pliocene sediments is not possible.
This characteristic change at 225 m in the Viernheim research borehole is comparable to the boundary at 176 m in borehole P 34 Ludwigs-hafen-Parkinsel (Weidenfeller & Kärcher 2008; Weidenfeller & Knipping 2008). There are also indications in the P 34 borehole of a palaeomagnetic change from the Gauss to Matuyama-Chron (Rolf et al. 2008). Rolf et al. also proposed that a characteristic change of the magneto-minerals from goethite (Pliocene) to greigite (Pleistocene) can be interpreted as a climatic signal. Pollen analysis from organic sediments just beneath and above the boundary at 225 m are planned to provide important information on the age of this section in the Viernheim research borehole.
Another key zone in the borehole is the Xb section (58.55 to 39.76 m). According to the hydrostratigraphic classification, this uppermost significant fine-clastic section of the borehole corresponds to a high resolution Obere Zwischenhorizont (OZH) in the sense of the hydrogeological mapping in the Rhine/Neckar zone (HGK 1999) or the sequence-stratigraphic equivalent to the Ladenburg Horizon (Symbolschlüssel Geologie Baden-Württemberg 2007, Villinger 2005). This section has been classified as part of the Cromerian Complex since Engesser & Münzing (1991) on the basis of its mollusc fauna. Palynological investigations by Knipping (2004, 2008) on various sections in the Mannheim-Ludwigshafen area led to the conclusion that the OZH contains several interglacial flora which are assigned to the Cromerian Complex. A correlation with the Eemian interglacial is ruled out. This means that Section Xb in the Viernheim borehole can also be assumed to be of Cromerian age. Important biostratigraphic indications of the Lower Pleistocene sections in particular are provided by the investigations conducted by Wedel (2008). No other chronostratigraphic interpretations of the Viernheim research borehole are possible at the current stage of the research.

Regional Trends

Regional trends can only be investigated at on the basis of characteristic horizons or boundaries which extend over larger areas. The horizons selected for this purpose are the Quaternary base as well as the top and base of Section Xb. This of course presupposes that the same unit or boundary could be selected for the correlation in the various wells and correlation could only use those boreholes with reliable stratigraphic logs, and gamma logs where possible (Tab. 3 and Fig. 10). Despite a large number of boreholes in the Hessisch part of the area of investigation, only eight boreholes in the Viernheim-Bensheim area are currently suitable for such a correlation.
The top of Section Xb dips to the south towards the centre of subsidence of the Heidelberg Basin. The thickness of the unit increases accordingly. The minor amount of data available on the Quaternary base indicates a similar picture with a major increase in thickness from north to SSE. Care must be taken for the difference in the quality of the samples. The absence of Section Xb in the Einhausen research borehole highlights a fundamental problem when look-

ing at the Pleistocene sedimentary fill in the northern Upper Rhine Graben: some horizons are very difficult to correlate, particularly towards the north. Despite high subsidence rates in this part of the northern URG as well, horizons are absent and can no longer be lithologically correlated even over short distances. Although correlation seems to function reasonably well in the centre of the Heidelberg Basin, there are also some fine-clastic horizons here which are only of restricted use for lithostratigraphic correlations. For instance, a fine-clastic horizon occurs in the Deponie Hirschländer borehole GWM1/03 at a depth of 21.58 to 25.65 m (thickness 4.07 m). This horizon is not seen in any of the surrounding boreholes. This is interpreted as indicating the presence of a very local channel deposit cut into the older sediments. Although easier to correlate regionally, the flood deposits of Section Xb become thinner as the distance from its subsidence centre increases, and even disappear in some cases. The conclusion drawn from this is that the use of sequence-stratigraphic models – as used for instance by Lang (2007) for the Hanau-Seligenstadt Basin (Fig. 1), a parallel structure to the URG – are more promising. Determining the A/S rates (A= accommodation space available for the sediment; S: sediment supply), and the interpretation of A/S domains can be used successfully in sedimentary basins with low subsidence rates. This approach needs to be tested first in sedimentary basins with higher subsidence rates, such as the northern URG.

Comments on supra-regional correlation and outlook

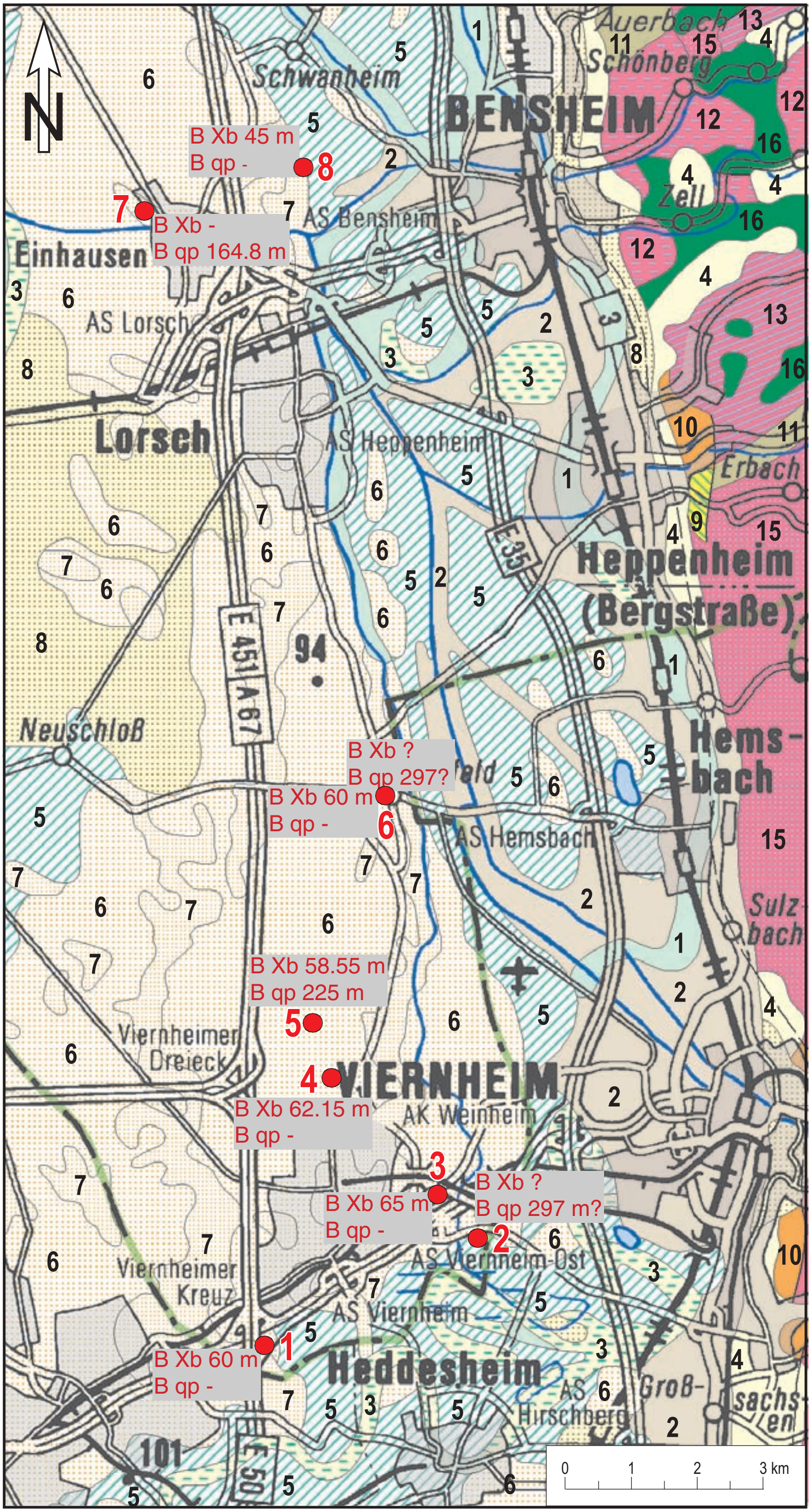
The Rhine as the link between the Alpine and North European glaciated areas also linked up different areas of provenance, accumulation areas and tectonic structural areas during the Quaternary (Preusser 2008; Westerhoff 2008). The typical sediments of the Rhenish Facies which are wide-spread in the northern Upper Rhine Graben also have equivalents downstream. At the northern edge of the URG in Wiesbaden (Fig. 1), deposits called the Mosbach Sands occur which have supra-regional significance because of their rich and typical fossil content (Boenigk 1977/78; Kahlke 2007; Keller 1999). In particular, the Graues Mosbach Horizon (nowadays called the Haupt-Mosbach-Subformation, Hoselmann 2007b) assigned to the Cromerian Complex, has significant macroscopic and sedimentary petrographic similarity with the Rhenish Facies in the Heidelberg Basin in the URG. The lower Middle Rhine zone contains the Hönningen Sands in the Mittelrhein-Hauptterassen Formation (Weidenfeller 2007), which is almost identical to the Rhenish Facies in the URG (Bibus 1980; Boenigk & Frechen 2006; Boenigk & Hoselmann 1991; Hoselmann 1996). The Rhine Group dominates the heavy mineralogy in these sediments, and carbonate contents of almost 30 % have been measured. These sediments are probably part of the Cromerian Complex. Similar sediments also occur in the upper Middle Rhine (Bibus & Semmel 1977). No other correlatable sediments are known in the other terraces of the Middle Rhine or in the Lower Rhine Embayment. The question therefore remains whether the sediments either did not accumulate in other times or whether they did not survive because they are easy to erode. In the area of the lower Middle Rhine, fluviatile terrace sediments occur in a series of terraces so that the uplift of the Rhenish Massif exposed the sediments to much stronger post-sedimentary erosion than the deposits in the Heidelberg Basin.

A more detailed explanation is required in the future of the type of mechanism which controlled the depositional cycles. A key role is played here by the uplift of the German Mittelgebirge and the subsidence of the URG, and in particular in this case the Heidelberg Basin. The cause for the start of a new cycle could also have been controlled by climatic conditions because periglacial environmental conditions were required to make these sediments available, particularly the coarse clastic sediments, which then accumulated in proximal locations. The interaction of sea level rises and falls on accumulation behaviour in the URG needs to

Table 3: Selected boreholes from the Viernheim-Bensheim area with the depths of the characteristic marker horizons. Petrographic descriptions of the flush drilled wells are uncertain.

Tab. 3: Ausgewählte Bohrungen aus dem Raum Viernheim–Bensheim mit der Tiefenlage charakteristischer Leithorizonte. Die petrographischen Beschreibungen der Spülbohrungen sind unsicher.

No. (Fig. 10)	Identifier Drilling method total depth (TD)	Gamma logging	Top layer Xb [m]	Base layer Xb [m]	Thickness layer Xb [m]	Base of the Quaternary sediments [m]
1	Deponie Hirschländer GWM1/03 dry drilling; TD 80 m	–	46	60	24	–
2	EWS Viernheim 2006/780 flush drilling (petrography uncertain); TD 300 m	–	?	?	?	297?
3	EWS Viernheim 2006/594 (2008) flush drilling; TD 140 m	X	45.5	65	19.5	–
4	STW Viernheim tube core drilling and flush drilling; TD 110 m	X	42.25	62.15	19.9	–
5	FB Viernheim B1/06 tube core drilling; TD 350 m	X	39.76	58.55	18.79	225
6	EWS Hüttenfeld 2007/581 flush drilling; TD 99 m	X	43	60	17	–
7	FB Einhausen C/01-BK4 tube core drilling; TD 205 m	X	–	–	0	164.8
8	WW Feuersteinberg GWM 75t flush drilling; TD 65 m	X	35	45	10	–


N
B Xb 45 m
B qp -
8
7
B Xb -
B qp 164.8 m
B Xb ?
B qp 297?
B Xb 60 m
B qp -
6
B Xb 58.55 m
B qp 225 m
5
4
B Xb 62.15 m
B qp -
3
B Xb ?
B qp 297 m?
B Xb 65 m
B qp -
2
1
B Xb 60 m
B qp -
Schwanheim
BENSHEIM
Auerbach
Schönberg
Zell
AS Bensheim
Einhausen
AS Lorsch
Lorsch
AS Heppenheim
Erbach
Heppenheim
(Bergstraße)
E 35
E 451/A 67
Neuschloß
Hems-
bach
AS Hemsbach
Sulz-
bach
Viernheimer
Dreieck
VIERNHEIM
AK Weinheim
AS Viernheim-Ost
Viernheimer
Kreuz
AS Viernheim
Heddesheim
AS Hirschberg
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0 1 2 3 km

1	Loam	Stagnant water sediments		Holocene		Quaternary
2	Loam, sand, gravel	Flood plain deposit				
3	Peat	Holocene organic sediment				
4	Clay, silt, frequently with cobbles, detritus and sand	Solifluction cover		Pleistocene		
5	Clay, loam	Flood plain loam				
6 7	Sand	Aeolian sand, [8] dune				
8	Gravel, sand	Terrace deposit				
9	Clay-silt, sand-gravel, marl	Oligocene, not subdivided		Oligocene	Older Tertiary	Tertiary
10	Sandstone, partly with cobbles, clay- and-siltstone		Lower	Buntsandstein	Lower Triassic	Germanic Triassic
11	Metasediments (predominantly biotite-plagioclase-gneiss, hornblende-gneiss, graphite schist, quartzite, marble, calc-silicate rock, garnet rock)	Metasediments, not subdivided				?Silurian-Devonian Early Ordovician
12	Flaser granitoid (predominantly oligoclase-K-feldspar-quartz-biotite-gneiss, mostly plagioclase-metablastic)	"Flaser gneiss" (synorogenic primary gneiss)				
13	Aplitic granitoid (plagioclase-K-feldspar-biotite-gneiss, biotite-muscovite-gneiss up to aplite granite)	"Younger biotite granite"				
14	Granite	Plutonic rocks of the Odenwald Mountains and Spessart				Early Carboniferous
15	Granodiorite, partly migmatic					
16	Diorite, quartz diorite, gabbro diorite, gabbro					Early Carboniferous (Frankenstein-Pluton, Higher Late Devonian)

Geological boundary

Faults, known

faults, assumed

State boundary

Scientific editing by members of the "Hessisches Landesamt für Umwelt und Geologie"

Status: 5. revised, digital edition; August 2007

Base data: General geological map of Hessen at a scale of 1:300,000 (1.-3. edition of F. RÖSING) and geological maps at a scale of 1:25,000

Topographic base of the map: Hessen at a scale of 1:200,000 (H200) reproduced with permission of the "Hessisches Landesamt für Bodenmanagement und Geoinformation". Verv.-Nr: 2006-3-81

Fig. 10: Distribution of various boreholes drilled recently in the southern Hessisches Ried used to evaluate "regional trends". The well locations are plotted on the geological base map of Hessen 1:300,000. The graben margin at the boundary to the crystalline Odenwald can be seen in the eastern part of the map; in the south-east with sedimentary rock remains of the lower Buntsandstein.
B Xb = Base section Xb in m below ground level; B qp = Base Pleistocene in m below ground level

Abb. 10: Verteilung verschiedener in den letzten Jahren abgeteufter Bohrungen im südlichen Hessischen Ried, die für die Auswertung „regionaler Trends" verwendet wurden. Die Bohransatzpunkte wurden in die Geologische Übersichtskarte 1:300.000 von Hessen eingetragen. Im östlichen Teil des Kartenausschnitts ist an der Grenze zum kristallinen Odenwald der Grabenrand zu erkennen; im Südosten mit Sedimentgesteinsresten des unteren Buntsandsteins.
B Xb = Basis Sequenz Xb in m unter GOK; B qp = Basis Pleistozän in m unter GOK

be clarified for this purpose. Rapid rises in sea level can also cause water to back up in the hinterland and possibly trap accumulation in front of the rising Rhenish Massif and lead to increased coarse clastic sedimentation in the southern Upper Rhine Graben and in the northern URG north of the Karlsruhe High to dominant fine-clastic sedimentation. Answering these questions requires detailed analysis of cores in the Heidelberg Basin because understanding the depositional processes and palaeogeographic development of this region and the fluviatile Rhine system is only possible in the high resolution deposits which are only found here in the thickest Quaternary sedimentary succession in the URG.

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Long sequence of Quaternary Rocks in the Heidelberg Basin Depocentre

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Abstract: A description and classification of the successions of the new scientific core drillings at Heidelberg is presented. Since 2002 drilling and research activities were ongoing in the Heidelberg Basin (HDB), as a mid-continental sedimentary archive within the Upper Rhine Graben (URG), Germany. The HDB is supposed to host one of the longest continuous successions of Quaternary sediments in Europe, due to continuous subsidence of the basin and sediment input from various sources. The HDB is about half-way between the Alpine source area of the Rhine and the North Sea. Here the Quaternary input is least affected by discontinuities due to climate events as alpine glacier meltdown events or periods of low sea level. Reversely, the low influence of climate leads to a larger tectonic control. The sedimentary succession of more than 500 m is considered as primarily controlled by tectonics, but with incorporated climate signals. For classification purposes, sediment provenance, lithofacies-associations, and the ratio of accommodation space and sediment input are used. Some biostratigraphic markers are also available. We suggest a sedimentary scenario where the overall fluvial environment is twice interrupted by lacustrine intervals. The accommodation space varies too: in one period it expands even beyond the eastern boundary fault of the HDB.

[Mächtige Abfolge quartärer Sedimente im Depozentrum des Heidelberger Beckens]

Kurzfassung: Die neue Forschungs-Kernbohrung aus Heidelberg wird beschrieben und gegliedert. Die Forschungs- und Bohraktivitäten im Heidelberger Becken (HDB) begannen im Jahr 2002; sie erschließen ein kontinentales Sedimentarchiv im Oberrheingraben (URG). Im HDB wird eine der längsten Sedimentabfolgen quartärer Sedimente in Europa erwartet, dank kontinuierlicher Subsidenz des Beckens in Verbindung mit kontinuierlichem Input von Sedimenten unterschiedlicher Herkunft. Das HDB befindet sich auf halber Strecke zwischen dem alpinen Einzugsgebiet des Rheins und seiner Mündung in die Nordsee. Eine kontinuierliche Sedimentation ist hier eher möglich als am Alpenrand mit seinen Schmelzwasser-Erosionsereignissen oder an der Küste mit ihren Meeresspiegelschwankungen. Dieser eher geringe Einfluss des Klimas hat zur Folge, dass die Tektonik eine umso größere Rolle bei der Steuerung der Sedimentation spielt. Die über 500 m mächtige quartäre Abfolge ist daher in erster Linie durch Tektonik kontrolliert, wobei Klimasignale ebenfalls

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erkannt werden können. Die hier vorgestellte Gliederung der Abfolge beruht auf Provenienz, Lithofazies und wechselnden Verhältnissen von Akkomodationsraum und Sedimentinput (a/s-ratio). Dazu kommen biostratigraphische Zeitmarken. Im skizzierten Sedimentations-Szenario dominieren fluviale Verhältnisse; dazwischen zwei lakustrine Abschnitte. Letztere sind verknüpft mit zunehmendem Akkomodationsraum, der in mindestens einer Zeitscheibe über die Grabenrandstörung hinweg sich bis in die Täler des Odenwalds erstreckt.

Keywords: Upper Rhine Graben, Heidelberg Basin, research borehole, lithofacies, sediment provenance, sequence stratigraphy, lithostratigraphy, biostratigraphy, differential uplift, subsidence.

1 Introduction

This paper summarises first results and impressions of the newly cored research borehole at Heidelberg. It is located at the depocentre of the „Heidelberg Basin“ (HDB), close to the eastern margin of the northern Upper Rhine Graben (URG). The probably largest and most complete Quaternary sediment succession along the Rhine has been exhibited, amounting to > 500 m. It proved to be a fairly continuous continental archive of the Quaternary in superposition and quite good resolution.

The sediments are strongly influenced by the input of the river Neckar, a major tributary of the Rhine which has its outlet into the URG within Heidelberg. Two other boreholes representing other parts of the HDB are the borehole of Viernheim in the geographic centre of the basin (Hoselmann 2008), and the borehole of Ludwigshafen at the western margin (Weidenfeller & Kärcher 2008, Rolf, Hambach & Weidenfeller 2008; Fig. 1). Their sediments are both dominated by input of the Rhine.

All three boreholes are part of a multidisciplinary research project (The Heidelberg Basin Drilling Project; Ellwanger et al. 2005, 2007, Gabriel et al. 2008). Its aims will be to identify the interaction of climate and tectonics as controlling mechanisms of sedimentation, describe properties and 3D architecture of the infill, and contribute to the correlation of alpine and north European Quaternary stratigraphy. This paper only contributes to the basics of this research, as is it primarily focused on the Heidelberg borehole.

2 Regional geological context

The northern URG contains a more or less continuous succession of Oligocene, Neogene and Quaternary sediments, which accumulated due to ongoing subsidence since Oligocene time (Dèzes, Schmid & Ziegler 2004, Duringer 1988, Gideon, Lopes Cardozo & Behrmann 2006, Rotstein et al. 2006, Schumacher 2002, Ziegler 1992). In the Quaternary, the subsidence increased towards the east, which led to a halfgraben architecture with a maximum sediment thickness at the eastern margin of the URG, i.e. the Heidelberg deep (Heidelberger Loch, location of the Heidelberg borehole, Bartz 1974). The western part of the Graben is slightly uplifted. As a result, the HDB lowlands are bordered in the east by the Odenwald highlands and the Kraichgau depression. West of the HDB, there is a widespread foothill landscape within the URG (Peters 2007), and the Pfälzerwald highlands at the western URG shoulder (Fig. 1).

The subsidence of the HDB is balanced by sediment input throughout the Quaternary. The primary sediment sources are the fluvial systems of Rhine and Neckar. The deposits mainly reflect this fluvial environment, but also include intervals dominated by local coarse debris input from the nearby highlands, and also some lacustrine intervals. The HDB succession is, therefore, not only an archive of the Quaternary stratigraphic evolution, but also of the varying sedimentary dynamics.

Fig. 1: Location of the UniNord boreholes in Heidelberg and other boreholes. The Eastern Boundary Fault (EBF) of the Upper Rhine Graben (URG) separates the lowland plains of the Upper Rhine from the adjacent highlands. The Heidelberg Basin (HDB) covers approximately the area between the present River Rhine and the EBF, extending some 10 – 15 km north and south of Heidelberg. The highlands east of the EBF are two-parted, the Odenwald anticline (highlands) in the north, and the Kraichgau syncline (lowlands) in the south. The Neckar valley is incised into the southern Odenwald highlands, as is the buried early Neckar valley at Mauer.

Abb. 1: Lokation der UniNord Bohrungen in Heidelberg und anderer Bohrungen. Die „östliche Hauptverwerfung“ (EBF) des Oberrheingrabens (URG) trennt die Oberrheinebene von den angrenzenden Mittelgebirgen. Das Heidelberger Becken (HDB) erstreckt sich zwischen dem heutigen Rheinlauf und der EBF, sowie, ausgehend von Heidelberg, jeweils 10 – 15 km nach Norden und Süden. Die Mittelgebirge östlich der EBF sind zweigeteilt, im Norden die Odenwald-Antikline (als Mittelgebirge) und im Süden die Kraichgau-Synkline (als Tiefland). Das Neckartal ist in den südlichen Odenwald eingeschnitten, wie auch das verlassene Neckartal bei Mauer mit seiner Talverschüttung.

3 Definitions and methods

3.1 Definition of „Quaternary“ in the Upper Rhine Graben (URG)

Some popular stratigraphic schemes of the URG are difficult for stratigraphers to apply, as chronostratigraphic terms are used to describe lithostratigraphic units (Table 1 in Gabriel et al. 2008). In this routine, „Quaternary“ and „Pliocene“ are defined by their sediment provenance (e.g. Bartz 1982, HGK Rhein-Neckar 1999). I.e. „Pleistocene“ Rhine sediments enclose material of alpine origin, „Pliocene“ sediments don't. This refers to a major event in the history of the alpine Rhine, when its course changed from „circumalpine“ towards the North Sea (Villinger 1998).
In the URG, this provenance transition is usually a very distinct and widely recognized boundary. The alpine origin of the sediments above is easely detectable by carbonate content and identification of pebbles of alpine origin. It can further be proved by heavy mineral analysis (Boenigk 1987, Hagedorn 2004). According to the few yet available chronostratigraphic markers, the boundary is considered diachronic. The markers come from the non-alpine sediments below. They are located close to the present river Rhine and 30 km apart: In Sessenheim (25 km north of Strasbourg) the transition is identified still within the uppermost Neogene (Boenigk 1987), in Marlen (5 km south of Strasbourg) at least post-Tiglian (Brost & Ellwanger 1991, Ellwanger 2003) or even post-Bavelian (Bludau 1998). In the far downriver Lower Rhine area, the provenance transition has been frequently detected as heavy mineral signal within the Pliocene Reuver Clay (Boenigk 1970, 1987, Boenigk & Frechen 2006, Kemna 2008, Kemna & Westerhoff 2007, Westerhoff 2004, 2008).
In this paper we use the lithostratigraphic scheme outlined below (chapter 3.3), which has been created some years ago to avoid confusion. We also use chronostratigraphic terms, but only when referring to chronostratigraphy and only based on chronostratigraphic data.

3.2 Sediment evaluation

In Applied Geology, the Quaternary sediment succession of the URG is up to now described as an alternation of units of coarse and fine-grained sediments (Kieslager, Zwischenhorizonte, Bartz 1982). These units are widely used in e.g. in hydrogeology, serving as aquifer resp. aquitard units. Most data in archives fit in this routine.
In this paper we describe the succession as lithofacies resp. lithofacies associations and identify genetic units (Fiebig 1999). We attempt to give a first interpretation of sedimentary cycles of various orders, stacking patterns and sedimentary control in different environments. Dealing with borehole cores of often quite coarse grained sediments, this is based primarily on first analysis of grain sizes, stratification, petrography, heavy minerals, carbonate content, pollen, molluscs, ichnofossils etc. Studies on stratification and textures are limited due to weak consolidation of the material.
We distinguish gravel, sand and fines (silt and clay) according to DIN 4022 and lithofacies terms according to Miall (1985, 1996). The succession is related to trends of the relative base level and the sediment input (a/s-ratio). They again depend on what is considered to ultimately control the sedimentary system: tectonic uplift and subsidence, compaction, but also effects of climate as intensified mechanical erosion.
The base level concept as applied here goes back to basic studies of Cross et al. (1993) and of Cross & Lessenger (1998). They combine Walther's law with sediment volume partitioning. This leads to a simplified way to regard sedimentary cycles as a function of accommodation space vs. sediment supply (a/s-ratio). In particular the grain size variations and changes in the recorded environment are interpreted, e.g. sequences with dominant pedogenesis represent very low input and high accommodation space, i.e. high a/s-ratio; in contrast to sequences with dominant sand preservation in the fluvial system where the fines are reworked, i.e. low a/s-ratio. The changes of increase and

decrease of the a/s-ratio are then used to identify the sequence stratigraphic frame which can be used for correlation.

3.3 Lithostratigraphy

The sedimentary succession is put in the frame of several lithostratigraphic units which were lately defined as formations and sub-formations (Fm, Sfm, Symbolschlüssel Geologie Baden-Württemberg 2007). They avoid the former mix-up with chronostratigraphy but, at the same time, try to continue to use major observations formerly registered. Primarily this concerns two observations: in the lower part of the succession the provenance change related to the alpine Rhine; and in the upper part (only northern URG) a specific boundary, revealing a wide-spread, externally controlled and abrupt change of lithofacies:

- Mannheim-Formation (upper unit), series of two or three sand cycles, low preservation potential of fines; topmost unit with increased ratio of local sand and gravel;
- Boundary: abrupt fine-coarse transition
- Kurpfalz-Formation (middle unit), series with basal coarse-fine-cycles of Rhenish provenance, followed by a sand-dominated section, and finally a widely recognized subunit of fines on top;
- Boundary: change of provenance;
- Iffezheim-Formation (lower unit), series of sand-to-mud cycles of local origin, usually including strongly weathered sediments.

The above patterns reflect the lithofacies of the central HDB. They are modified by local input, in this case of the Neckar close to Heidelberg. Please note that in the frame set up by these definitions,

- Provenance plays no part with regard to the upper boundary (Kurpfalz-Formation vs. Mannheim-Formation);
- Lithofacies plays no part with regard to the lower boundary (Iffezheim-Formation vs. Kurpfalz-Formation); and
- Chronostratigraphy plays no part with regard to both boundaries.

4 The Heidelberg Cores – Description and basic classifications (Litho- and Biostratigraphy)

4.1 Some general remarks

The Heidelberg research boreholes are the deepest in the project, representing the depocentre on the eastern margin of the HDB. They are located just north of the Campus of Heidelberg University, still close to the mouth of the River Neckar in downtown Heidelberg, and situated on the alluvial fan of the Neckar. For technical reasons, a first borehole was cored to 190 m, a second borehole from 184 to 500 m (UniNord 1+2). The two sites are only 300 m apart and are easily correlated (Fig. 2). Their combined depth of 500 m exhibits Quaternary sediments down to ~ 500 m which is more than originally predicted (before drilling the chronostratigraphic Plio- Pleistocene transition was expected around 400 m, i.e. we intended to recover 400 m cores of Quaternary sediments, plus 100 m of Pliocene sediments).

We present a condensed lithostratigraphic description and classification of the sediments, including some remarks on

- sediment provenance, derived from pebble and heavy minerals analysis;
- the sedimentary environment;
- the few already available biostratigraphic markers, derived from pollen analysis, that are used to set up a chronostratigraphic frame;
- and depositional trends.

Following the conventional technique of core documentation, the major units are in order from top to bottom; but subunits in upward direction. A detailed description including further data will be published later in a special volume of LGRB Informationen (Regierungspräsidium Freiburg, www.rp-freiburg.de).

The sediment succession is provisionally subdivided in three large units according to the above lithostratigraphic terms. At UniNord they were identified as follows:

- Mannheim-Formation from 56 to 0 m; as a series dominated by coarse gravels, with layers of diamicton and fines, including a well preserved fossil soil;

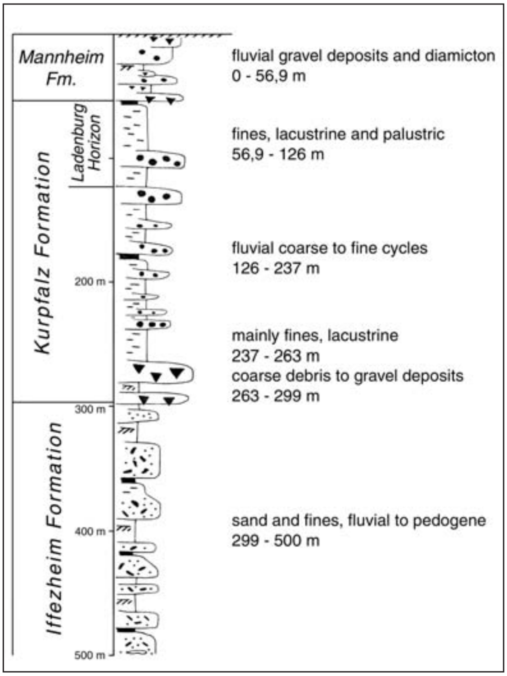

Fig 2: Overview of the sediment succession of the Heidelberg deep down to 500 m, comprised from the UniNord boreholes of 2006 (interval from 0 to 190 m) and of 2008 (interval from 184 m to 500 m). Lithostratigraphic frame, major lithologies and sedimentary environments. Legend cf. Fig. 3.

Abb. 2: Übersicht der Sediment-Abfolge im Heidelberger Loch bis 500 m Tiefe, zusammengesetzt aus den Bohrungen UniNord aus 2006 (Abschnitt von 0 bis 190 m) und aus 2008 (Abschnitt von 184 m bis 500 m). Lithostratigraphischer Rahmen, vorherrschende Lithologie und Ablagerungsmilieu. Legende vgl. Abb. 3.

- Boundary: abrupt transition of fine-coarse sedimentation
- Kurpfalz-Formation from 299 to 56 m; as a series with coarse debris at the basis (subunit K1); a two-parted main section with coarse debris and gravel, sand and fines in the middle part; and a fine sediment dominated section on top;
- Boundary: change of provenance and abrupt transition of fine-coarse sedimentation
- Iffezheim-Formation from >500 to 299 m; as a cyclic alternation of white-sand to clay and dark sand, altogether of non-alpine origin.

4.2 Mannheim Formation at UniNord

The Mannheim-Formation at UniNord covers the interval from 0 to 56 m. The sediments are composed of about 75 % coarse debris and gravel, 10 % sand, 5 % fines, and 10 % diamicton. Fluvial gravels dominate. However, the succession begins and ends with a layer of coarse debris, the upper one resembling the alluvial fan of the Neckar which presently undergoes erosion and terrace formation. Within the gravels there are insertions dominated by diamicton; one of them grading into fines with a fossil soil.

The succession is stratified as follows (cf. Fig. 3):

- 0 – 12 m coarse debris with boulders, gravel and layers of sand;
- 12 – 26 m fluvial gravel with some layers of sand;
- 26 – 34 m diamicton with sand cover;
- 34 – 38 m diamicton grading into mud with fossil soil ;
- 38 – 46 m fluvial gravel;
- 46 – 48 m diamicton;
- 48 – 55 m fluvial gravel;
- 55 – 56 m coarse debris and gravel;

Provenance: The petrographic spectra of the gravels reflect the up-river catchment of the present Neckar valley passing through the Odenwald highlands. There are large components of the nearby Buntsandstein which are coarse and poorly rounded. The Muschelkalk components are usually finer and better rounded; however, one boulder occurs at the basis of the unit at 56 m. Some small components come from the far distant Neckar catchment, i.e. the Jurassic of the Swabian Alb. The crystalline basement with the nearby major exposure below Heidelberg castle is only poorly represented. – Most sand and fines are also of Neckar provenance, with the exception of several sand-rich strata resembling traces of Rhenish provenance by their instable heavy mineral composition. They are very well sorted and therefore supposed to come from reworked eolian input, alike to the nearby dunes, and may represent elder phases of cold climate (26 – 29 m).

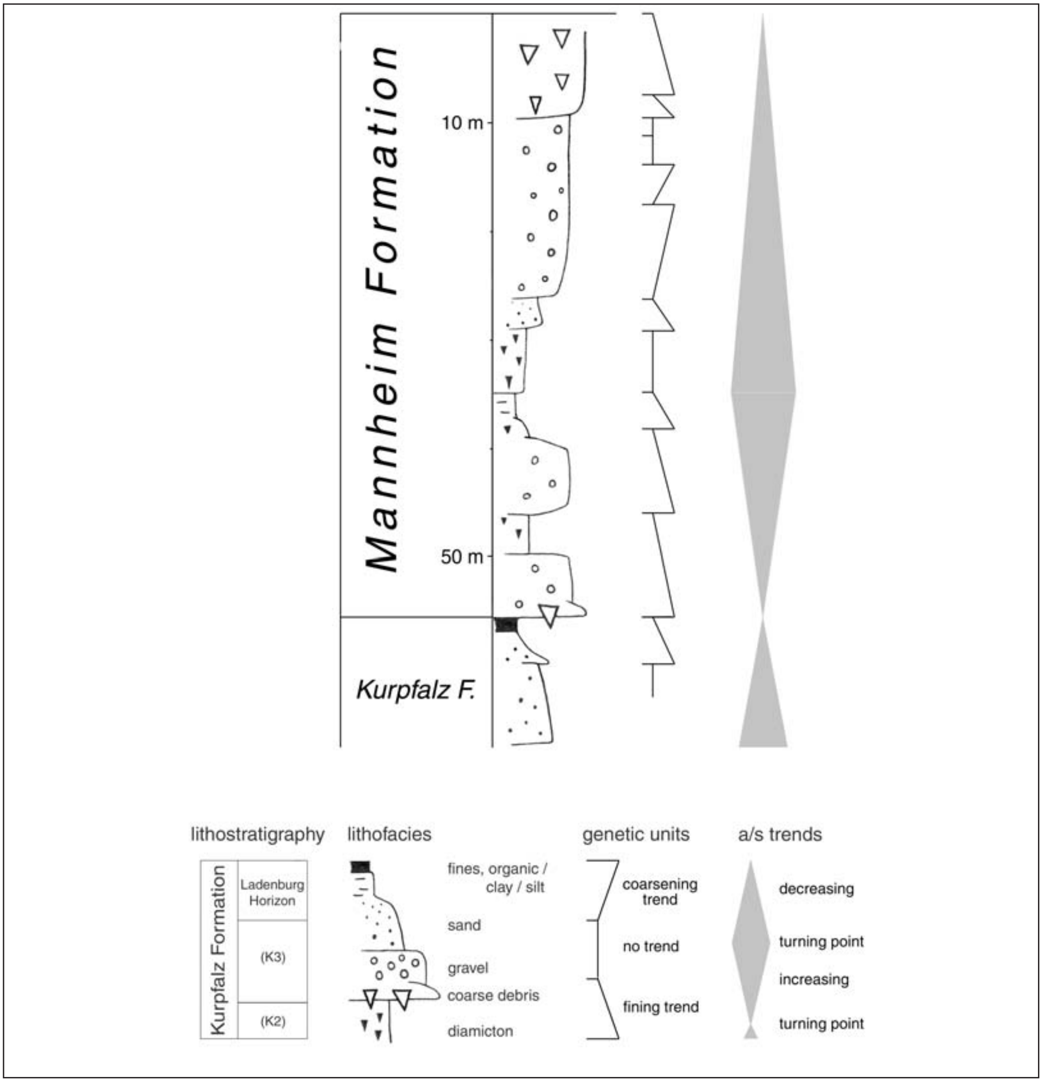

Fig. 3: The sediment succession of the Mannheim-Formation in the Heidelberg UniNord research borehole (location Fig. 1).
Centre: Stratigraphic succession as Lithofacies log (schematic), genetic units; Left: Lithostratigraphic interpretation; Right: Sequence stratigraphic trends (increasing and decreasing a/s-ratio).
The succession is dominated by coarse debris flows and proximal fluvial gravels, but also includes insertions of matrix-rich diamicton and fine sediments. – Further details on the stratigraphic succession, provenance, chronostratigraphic markers and sedimentary environment see text.

Abb. 3: Die Sedimentfolge der Mannheim-Formation aus der Forschungsbohrung Heidelberg UniNord (Lokation Abb. 1):
Mitte: Stratigraphische Abfolge als schematisches Lithfazieslog, genetische Einheiten; Links: Lithostratigraphische Interpretation; Rechts: Sequenzstratigraphische Trends (zu- und abnehmendes a/s-Verhältnis).
Die Abfolge wird beherrscht von groben Debris-Flows und proximalen Flussschottern; sie enthält auch Einschaltungen von Matrix-reichen Diamikten und Feinsedimenten. – Weitere Angaben zur Schichtenfolge, Provenienz, chronostratigraphischen Marken und Ablagerungsmilieu im Text.

Sedimentation: The depocentre of the HDB corresponds with the alluvial fan of the Neckar. The genetic units in intervals with coarse debris and fluvial gravels match well with this proximal setting (Fig. 3). One major interval with diamicton, fines and pedogenesis, occurs all over the depocentre (HGK 1999). As a result, the Mannheim-Fm shows an overall coarse – fine – coarse trend, going along with a first increasing then decreasing a/s-ratio. Any further interpretation needs a chronostratigraphic frame.

Chronostratigraphy: No chronostratigraphic markers are yet available. As the underlying unit (Ladenburg-Subformation) is supposed to date from the Cromerian, post-Cromerian ages are expected. The fossil soil at 34 m is quite well preserved, dividing the succession into an upper and a lower part. Their interpretation remains open (last and penultimate glaciation, effects of loading and compaction).

Summary and interpretation: The major part of the Mannheim-Formation at the Heidelberg UniNord borehole is built up by coarse sediments representing the proximal lithofacies of the Neckar alluvial fan. This is an input-controlled system which strongly depends on sediment supply from the nearby Odenwald highlands. As preservation in superposition is discontinuous, due to lateral shifting within the fan, the subsidence of the basin plays only a minor part.

4.3 Kurpfalz Formation at UniNord

The Kurpfalz-Formation at UniNord covers the interval from 299 to 56 m, i.e. its thickness amounts to 243 m. It is composed of 35 % debris and gravel, 20 % sand, and 45 % fines. There is a continuous background supply and preservation of fine sediments (lacustrine, fluvial overbanks), interrupted by three major intervals with coarse debris and gravel input (fluvial bedload, mass flow). Accordingly it is subdivided into lithostratigraphic subunits.
The uppermost subunit (interval 56 to 126 m, Ladenburg-Subformation) is dominated by fine sediments. The subunit from 126 to 237 m (subunit K3) subsumes two pulses of coarse input (intervals 126 – 168 m and 189 to 206 m), but throughout with layers of fines and sand. The next subunit from 237 to 263 m is again wholly dominated by fine sediments (K2). Some genetic units grade into dark fines (organic), others into clay with evidence of pedogenesis and ichnofossils. The lowermost subunit (263 – 299 m, K1) is dominated by massive coarse debris (263 – 288 m) which represents the termination of a coarsening-up trend that begins with red sands below the Formation boundary at 316 m. The definition of the lower boundary of the Kurpfalz-Formation is, as indicated above, not a matter of the local cycle architecture but of provenance. The lowermost signal of instable „alpine“ heavy minerals has been identified at 292 m; we suggest the Formation-basis at 299 m.

The sediment succession of the Kurpfalz-Formation is stratified as follows (Fig. 4):

Ladenburg-Subformation from 56–126 m = 70 m (20 % gravel, 10 % sand, 70 % fines)

• 56 – 67 m	graded sand to fines and fossil peat, fluvial, some sand from eolian input and fluvially reworked;
• 67 – 74 m	massive fines, lacustrine;
• 74 – 80 m	graded sand to fines;
• 80 – 83 m	silt and clay, ichnofossils, fossil soil, fluvial environment;
• 83 – 89 m	massive fines, lacustrine;
• 89 – 92 m	gravely sands, ?diamicton;
• 92 – 101 m	gravel, some sand from eolian input and fluvially reworked, ?diamicton (no or poor cores);
• 101 – 103 m	fines and sand, gravely, ?diamicton (poor cores);
• 103 – 109 m	coarse debris, gravel, sand, ?diamicton (poor cores);
• 109 – 126 m	massive fines, at the basis with coarse components, lacustrine;

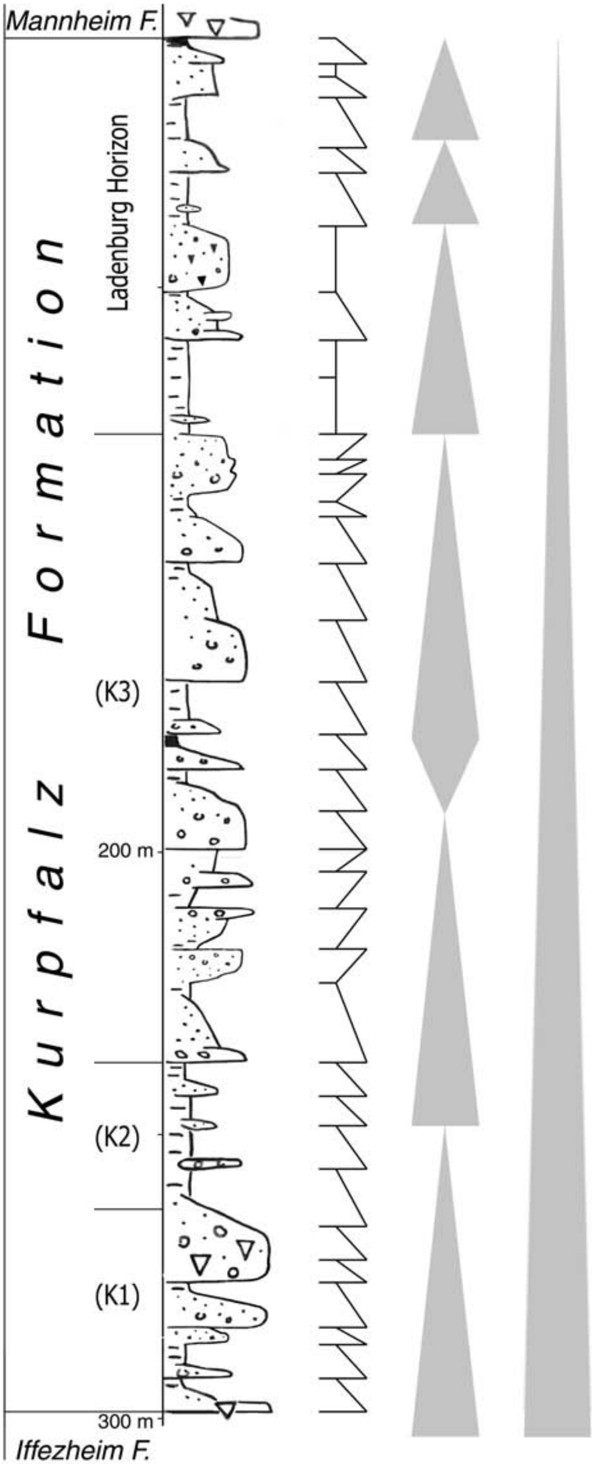

Fig 4: The sediment succession of the Kurpfalz-Formation in the Heidelberg UniNord research borehole (location Fig. 1).

Centre: Stratigraphic succession as Lithofacies log (schematic), genetic units;

Left: Lithostratigraphic interpretation (Formation and sub-units);

Right: Medium and large scale sequence stratigraphic trends.

The succession begins with sediments reflecting a lacustrine environment, with and without coarse mass flow insertions (K1, K2). It grades up into fluvial overbanks and gravels (lower K3) and a prograding system of fluvial gravels (upper K3). After abrupt change, the pattern is twice repeated on smaller scale (Ladenburg-Horizon). – Further details on the stratigraphic succession, provenance, chronostratigraphic markers and sedimentary environment see text. Legend cf. Fig. 3.

Abb. 4: Die Sedimentfolge der Kurpfalz-Formation aus der Forschungsbohrung Heidelberg UniNord (Lokation Abb. 1):

Mitte: Stratigraphische Abfolge als schematisches Lithfazieslog, genetische Einheiten

Links: Lithostratigraphische Interpretation (Formation und Untereinheiten);

Rechts: Sequenzstratigraphische Trends mittlerer und großer Ordnung.

Die Abfolge beginnt mit lakustrinen Sedimenten, zunächst mit, dann ohne Grobsediment-Einschaltungen (K1, K2). Darüber fluviale Overbank-Sedimente und Schotter (K3 unterer Teil) und schließlich ein progradierendes System fluvialer Schotter (K3 oberer Teil). Nach einem abrupten Wechsel wiederholt sich dasselbe Muster in kleinerer Ordnung zwei Mal (Ladenburg-Horizont). – Weitere Angaben zur Schichtenfolge, Provenienz, chronostratigraphischen Marken und Ablagerungsmilieu im Text. Legende vgl. Abb. 3.

Section (K3) from 126 – 237 m = 111 m
(35 % gravel, 30 % sand, 35 % fines)

- 126 – 138 m sand, gravel, debris (no or poor cores recovered);
- 138 – 152 m sand and gravel with some fines (no or poor cores recovered);
- 152 – 168 m sand and gravel (no or poor cores recovered), basis of subunit K3b;
- 168 – 179 m massive fines upon insertion of sandy gravel;
- 179 – 185 m cycle of gravel-sand-fines-peat;
- 185 – 206 m basal debris, gravel, red sand and fines, K3a;
- 206 – 211 m gravely sand and fines;
- 211 – 215 m sand;
- 215 – 217 m fines, fossil soil;
- 217 – 222 m gravel, debris;
- 222 – 227 m fines, fossil soil;
- 227 – 234 m grey and red sand;
- 234 – 237 m coarse debris grading into dark fines (organic);

Section (K2) from 237 – 263 m = 26 m
(10 % gravel, 15 % sand, 75 % fines)

- 237 – 263 m fines, sandy to muddy, with few insertions of sand (254 – 257), gravel (247 – 248) and debris (258 – 259), fossil soils;

Section (K1) from 263 – 299 m = 36 m
(60 % gravel and debris, 10 % sand, 30 % fines)

- 263 – 287 m debris of coarse gravels and some boulders, few layers of sand and fines;
- 287 – 297 m fines, silt and clay with ichnofossils, sand layers;
- 297 – 299 m debris of coarse gravels and some boulders.

Provenance: The sediment input in the Kurpfalz-Formation of the UniNord succession is classified in sediments of Rhine origin (i.e. comprising a signal of the alpine source area), of Neckar origin, and of very local origin. They may be subdivided in:

(a) fines and sand of the Rhine (proven by instable heavy mineral ratio > 50 %);
(b) local or Neckar fines and sand (instable heavy mineral ratio < 50 %);
(c) gravel of the Neckar (pebbles of Buntsandstein, Muschelkalk and Jurassic); and
(d) coarse debris and gravel of the nearby Odenwald (mainly Buntsandstein, some crystalline and Muschelkalk).

The sediments of the Ladenburg-Subformation belong primarily to the „fines and sands of Neckar or local origin“. There are exceptions at the top of two lacustrine intervals, where minor sand pulses of Rhine origin are identified by their instable heavy mineral content. Presently we interpret this to be fluvially reworked eolian input. – The Ladenburg-deposits of UniNord are contemporaneous with similar deposits all over the HDB which are usually of Rhine origin. They also correlate with the upstream buried valley infill at the discovery site of the *Homo heidelbergensis* located near to the village of Mauer, some 15 km southeast of UniNord (Löscher 1996). From this it follows that the sediment of this subunit covered the whole HDB, and extended beyond the Eastern Boundary Fault (EBF) of the URG. I.e. the nearby Neckar valley within the Odenwald highlands is also, as a drowned valley, part of the basin.

The subunits K1 and the lower part of K3 show strong evidence of periodical fluvial input from the alpine Rhine, with continuous input from the Neckar upheld. In K1, the arrival of the Rhine and the preservation of fines even when alternating with coarse local sediments indicate a strongly increasing a/s-ratio. In K2, only sand on fines of non-Rhine origin are yet identified. The K3 succession begins with an alternation of local and Rhine input. Then the local input is gradually replaced by supply from the Neckar, and still further up the input from the Rhine terminates. From 190 m upwards only sediments of Neckar provenance are left.

The three intervals of coarse debris and gravel (subunits K1 and K3) refer to expanding erosion into the Odenwald, probably due to uplift.

There is always an overall dominance of coarse Buntsandstein, but the ratio of the supplementary components varies (Muschelkalk, crystalline). The first coarse pulse (299 – 297 m, basis of K1) contains much local crystalline (Heidelberg Granite). The main pulse (287 – 263 m) is mainly Buntsandstein, but with an upward increasing ratio of Muschelkalk; i.e. the sediment source is first „downtown Heidelberg", then expanding towards the Muschelkalk scarp. – Two coarse intervals of fluvial gravels follow (206 – 189 m and 168 – 126 m, subunit K3). Within the latter a first small then increasing ratio of Jurassic is present, and there are some layers where the Muschelkalk components dominate. This is also characteristic regarding some correlative gravely insertions in the succession of the Viernheim sister drilling (interval 180 to 80 m, Hoselmann 2008).

Sedimentation: The overall fluvial evolution of the UniNord succession is interrupted in the Kurpfalz-Formation by intervals of lacustrine conditions and by intervals of strong supply of mass flows. Our interpretation as a lacustrine environment is based upon the abrupt occurance of coarse-grained debris flows within the fine-grained background sedimentation. In some parts of the succession, even matrix supported mass flow deposits including boulders and cobbles occur (high density mass flows). The abrupt alternation of mass flow- and background-sedimentation is a clear indication for lacustrine deposition in a lake system with a minimal water depth of several meters.

The first lacustrine interval is at the basis of the Formation where mass flow deposits of coarse debris are embedded in fines, with almost no transition (subunit K1). It carries on in subunit K2 with few coarse layers in the fines. Eventually the lacustrine sedimentation terminates, first indicated by fossil soils in the fines (transition of subunits K2 to K3), then by cycles of fluvial gravels to fines (subunit K3). The lower gravel seems to represent a local event; the upper reflects a long and overall coarsening-up series of a prograding fluvial system. – The transition to follow, from fluvial gravels to the fines of the Ladenburg-Subformation, is again very abrupt. The fines are massive; again with insertions of mass flow deposits (here the components are well rounded i.e. reworked from the gravels). This again represents a lacustrine environment. Towards the top of these fines, the environment migrates back towards fluvial, first visible in traces of plant roots and ichnofossils, still within the fines, then by re-establishing the prograding fluvial system (lacustrine-to-fluvial cycle from 126 to 89 m = 37 m). In the upper part of the Ladenburg-Subformation, two more lacustrine to fluvial transitions are identified (89 – 74 m = 15 m; and 74 – 56 m = 18 m). They range from massive fines up to graded sands, i.e. they comprise no gravely sediments. Further up, the lacustrine to fluvial cyclicity is drowned by the input of the Mannheim-Formation.

The Kurpfalz-Formation shows an overall decreasing a/s-ratio throughout the succession, with various symmetrical and asymmetrical cycles of lower order (Fig. 4). The maximum accommodation space is given in the first lacustrine cycle (K1, K2), which hosts not only coarse local debris but also alpine sands of the Rhine. The alpine influence is then pushed back by prograding coarse-grained fluvial Neckar deposits (K3).

Chronostratigraphy: Some biostratigraphic markers based on pollen analysis are already available. They are preliminarily interpreted.

- At 57 – 70 m and at 82 – 85 m, „coniferous forest": Interpretation: cool to cold „interstadial" climate.
- At 81 – 82 m and at 87 m, „typical middle Pleistocene pollen spectra" but no *Fagus* and no early Pleistocene species. Interpretation: Cromerian.
- At 162 – 163 m, pollen spectra with *Pinus*, *Picea* and *Tsuga*, no *Carya*, no *Eucommia.* Interpretation: Bavelian (per se uncertain, but in the succession quite likely).
- At 180 – 208 m, pollen spectra with *Tsuga* and *Pterocarya*. Interpretation: Waalian (certain, Hahne, Ellwanger & Stritzke 2008).

- At 212 – 249 m „coniferous forest“: Interpretation: rather cold climate, may match with the Eburon cold period.

The Cromerian age of the Ladenburg-Subformation was first published by ENGESSER & MÜNZING (1991); also the „Maurer Sande“ are of Cromerian age (LÖSCHER 1996).

Summary and interpretation of the Kurpfalz-Formation: The succession of the Kurpfalz-Formation at UniNord, within its upper „sequence“-boundary and its lower „provenance“-boundary, comprises one overall large scale cycle, from a basal lacustrine environment up to a large and input controlled subunit of prograding fluvial gravels. The fines to follow are, although in parts lacustrine and related to a final pulse of subsidence, only of local importance. We suggest this has to do with the pattern of Rhine sediments through time in the HDB. This is confirmed by the sister boreholes of the Heidelberg project at Ludwigshafen and Viernheim, where, as it seems, the Rhine signal comes, in each case, at a different chronostratigraphic level.

- In Heidelberg, the overall depocentre of the HDB, the Rhine signal begins at 299 m (Eburonian) and ends at 190 m (Waalian);
- In Ludwigshafen at the western margin of the HDB, the Rhine signal begins at 177 m close to the Pliocene-Pleistocene transition (WEIDENFELLER & KÄRCHER 2008 and WEIDENFELLER & KNIPPING 2008), then comes to a standstill (increase of local sediments with only stable heavy minerals) at 137 – 127 m and 109 – 97 m (Waalian);
- In Viernheim at the geographic centre of the HDB, the Rhine signal begins at 220 m (HOSELMANN 2008, KNIPPING 2002, 2008). As discussed above we suggest correlating a subunit of prograding gravels from Heidelberg (Bavelian) with the 80 – 180 m interval at Viernheim. This leaves 40 m with little evidence of any greater hiatus. From all this we suggest the provenance change to happen in the Waalian.

The above may be interpreted as „alpine“ Rhine sediments migrating in three steps through what later became the HDB: This story begins in Ludwigshafen close to the Pliocene-Pleistocene transition; then it continues in Heidelberg in the Eburonian; and finally comes to Viernheim in the Waalian.

The subunit of prograding gravels (K3, Bavelian) appears to be the first unit covering the HDB in its present extent as a whole, as do the above units of the Ladenburg-Subformation and the Mannheim-Formation. Below the gravels (K3) there is a patchwork of local units which are difficult to correlate. Here the units including alpine Rhine sediments may be of small extend. Their west-to-east migration (from Ludwigshafen to Heidelberg) seems to be subsidence-controlled, as a result of the Halfgraben architecture. Their return back west to Viernheim is related to Neckar input. The upper units covering the entire HDB are related to input pulses of Rhine and Neckar which include potentially increased sediment volumes during the Pleistocene glaciations.

All sediments below the „alpine“ Rhine, regardless of their chronostratigraphic position, are not part of the Kurpfalz-Formation. They belong, to the Iffezheim-Formation.

4.4. Iffezheim Formation at UniNord

The Iffezheim-Formation at UniNord covers the interval from >500 to 299 m, i.e. >202 m. It is a cyclic alternation of fluvial deposits with an average composition of 55 % sand, and 45 % fines. The succession is subdivided in several lithostratigraphic subunits, according to lithofacies variations. They are dominated by sand at 316 to 382 m (I5); by fine sediments at 382 to 411 m (I4); again by sand at 411 to 452 m (I3); fine sediments at 452 to 467 (I2); and finally by sand at 467 to >500 m (I1). The uppermost subunit at 299 to 316 m (I6) resembles the transition to the lacustrine environment and to the onset of coarse local debris of subunit (K1).

The main fluvial lithofacies are:

- Grey, coarse to medium-grained sands. They contain only few gravely components, the small pebbles being well rounded and often with weathering halos. Quite frequently there are other coarse components, as pieces of wood of various size (in the cores with diameters up to 25 cm), but also reworked pieces of fine sediment, ranging from small rounded pieces up to large strata. Their original stratification may be preserved, including organic-rich laminae or even peat. They were probably in a frozen state during transport.

- White, fine to medium-grained sands, usually very well sorted. They either alternate with the grey sand lithofacies, or grade into green silt with sandy laminations, and finally into the silt and clay cycles.
- Clay-rich overbank fines, forming sequences of green and sandy silt grading into clay-rich silt up to almost pure clay, usually speckled with brownish (wet) and reddish (dry) colours resembling pedogenesis. Colours are intense, apart from the transition to the Kurpfalz-Formation where they become dark and gloomy. The sequences are rich in ichnofossils, in some layers also in authigenic grains (authigenic siderite, Dr. Martin, Freiburg). Some are fractured due to diagenetic compaction.

The sediment succession of the Iffezheim-Formation is stratified as follows (cf. Fig. 5):

Section (I6) from 299 to 316 m = 17 m
(55 % sand and 45 % fines)

- 299 – 305 m dark fines, sandy silt to clay;
- 305 – 316 m massive dark grey sand and graded dark red sand;

Section (I5) from 316 – 382 m = 66 m
(65 % sand and 35 % fines)

- 316 – 323 m fines (sandy silt to clay with organic-rich top);
- 323 – 329 m brightly coloured fines (sandy silt to clay);
- 329 – 340 m alternation of
  - grey sand with reworked wood and fines, and of
  - white sand with kaolin;
- 340 – 342 m brightly coloured silt and clay, ichnofossils;
- 342 – 351 m grey sand with reworked wood and fines;
- 351 – 382 m grey sand with reworked wood and fines;

Section (I4) from 382 – 411 m = 29 m
(10 % sand and 90 % fines)

- 382 – 399 m fines, green silt to coloured clay with ichnofossils and brown and red fossil soils;
- 399 – 402 m white sand and grey silt;
- 402 – 411 m brightly coloured fines, green silt to coloured clay with ichnofossils and brown and red fossil soils;

Section (I3) from 411 – 451 m = 40 m
(70 % sand and 30 % fines)

- 411 – 421 m grey sand with reworked wood and fines, grading into white sand;
- 421 – 425 m white sand grading into silt and clay with ichnofossils;
- 425 – 440 m alternation of
  - grey sand with reworked wood and fines, and of
  - white sand with kaolin matrix;
- 440 – 443 m brightly coloured silt and clay with ichnofossils;
- 443 – 451 m alternation of
  - grey sand with reworked wood and fines, and of
  - white sand with kaolin matrix (445 – 447);
  - fines, laminated with white sand (443 – 445);

Section (I2) from 451 – 467 m = 16 m
(almost 100 % fines)

- 451 – 467 m brightly coloured fines, green silt to coloured clay with ichnofossils and brown and red fossil soils;

Section (I1) from 467 – 500 m = 33 m
(80 % sand and 20 % fines)

- 467 – >500 m grey sand with reworked wood and fines;

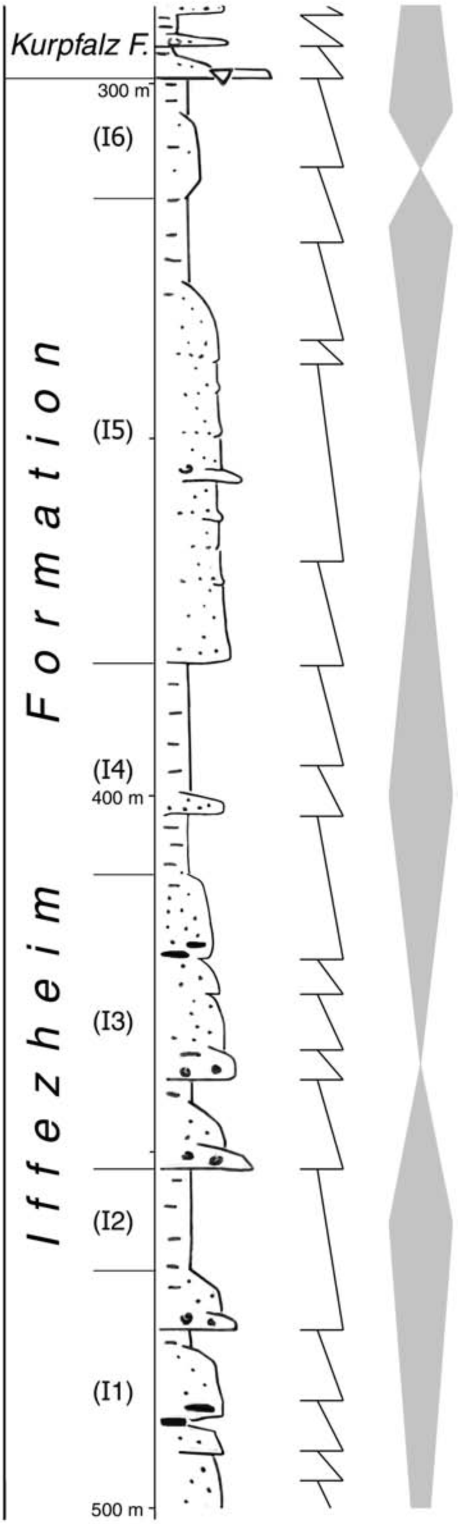

Fig. 5: The sediment succession of the Iffezheim-Formation in the Heidelberg UniNord research borehole (location Fig. 1).
Centre: Stratigraphic succession as Lithofacies log (schematic), genetic units;
Left: Lithostratigraphic interpretation (Formation and sub-units);
Right: Sequence stratigraphic trends (increasing and decreasing a/s-ratio).
The succession (I1 - I5) is composed of alternating fluvial bedload sands and overbank silt and clay. The sands contain large pieces of reworked overbank fines, the silt and clays are frequently altered by ichnofossils and pedogenesis. The uppermost unit (I6) includes proximal local sand insertions reflecting the beginning of local mass flow as in unit K1. – Further details on the stratigraphic succession, provenance, chronostratigraphic markers and sedimentary environment see text. Legend cf. Fig. 3.

Abb. 5: Die Sedimentfolge der Iffezheim-Formation aus der Forschungsbohrung Heidelberg UniNord (Lokation Abb. 1):
Mitte: Stratigraphische Abfolge als schematisches Lithfazieslog, genetische Einheiten
Links: Lithostratigraphische Interpretation (Formation und Untereinheiten);
Rechts: Sequenzstratigraphische Trends (zu- und abnehmendes a/s-Verhältnis).
Die Abfolge (I1 - I5) besteht aus fluvialen Sanden (bedload) und schluffig-tonigen Overbank-Schichten. In den Sanden sind große Feinsedimentstücke aufgearbeitet, während die Overbanks durch Spurenfossilien und Bodenbildung verändert sind. In der obersten Einheit (I6) sind proximale Lokalsande eingeschaltet, die zu den Massflows der darüber folgenden Einheit K1 überleiten. – Weitere Angaben zur Schichtenfolge, Provenienz, chronostratigraphischen Marken und Ablagerungsmilieu im Text. Legende vgl. Abb. 3.

Provenance: The „local“ i.e. non-alpine origin of the sediments determines their allocation to the Iffezheim-Formation. This is primarily based on heavy mineral analysis. Many of the few coarser components are of Buntsandstein origin, as are several layers of red sands. – The provenance of the other sediments remains uncertain. The well sorted white sands are probably far transported, but this may be an inherited feature if they are reworked from nearby Neogene sands. The grey sands are related to various sources, including crystalline and Buntsandstein (Odenwald? Black Forest?). They seem confined to a fluvial system close to the eastern margin of the URG. The source of the silt and clay is again undetermined, probably nearby Neogene.

Sedimentation: By alternation of the grey sand lithofacies and the silt-to-clay lithofacies, several genetic units are stacked to symmetrical cycles of increasing and decreasing a/s-ratios. Within the fines, the turning points often coincide with intensive pedogenesis i.e. almost no input; within the sands they coincide with sections where large pieces of reworked fines indicate a/s minima. These bedload-dominated units represent the greater part of the succession. The preserved cycles are in the 10 to 50 m order. – The minima of accommodation space are likely to be related with increasing sediment supply, maybe due increased sediment volumes as a result of colder climate (some of the reworked fines are still stratified, they may have been frozen when redeposited). As opposed to this the sediment input is generally much reduced in silt-clay sections, with ichnofossils and traces of more or less reworked fossil soils. Preservation is primarily related to local subsidence of the depocentre, but differentiated uplift within and at the northern margin of the URG may also be involved.

Chronostratigraphy: Some biostratigraphic markers based on pollen analysis are already available. They are preliminarily interpreted.

- At 312 m, „open coniferous forest with herbs“. Interpretation: cool to cold climate (per se indifferent, but in the succession most likely Eburonian).
- At 316 m, „*Pinus*-dominated coniferous forest“. Interpretation: cool to cold climate, could match with the Eburon cold period.
- At 358 – 359 m, reworked strata. They host a pollen spectrum with > 30 % „tertiary taxa“ immediately overlying a typical „early Pleistocene pollen spectra“ with *Fagus* but no *Tsuga.* Interpretation: reworked Reuverian (Reuverian A) overlying reworked late Tiglian. Deposition age: late Tiglian to early Eburon.
- At 417 – 500 m (lowest sample at 499.94 m): several typical „early Pleistocene pollen spectra“ with *Fagus* and tertiary taxa increasing downward, no *Tsuga.* Interpretation: Tiglian (certain) in stratigraphic superposition.
- At 481 m: „*Pinus*-dominated coniferous forest“. Interpretation: cooler climatic period within the Tiglian (possibly Tiglian B, sensu ZAGWIJN 1963).
- There are no hints for in-situ sediments from the Pretiglian or Reuverian period. The reworked sample at 358 m illustrates the pollen spectra to be expected from in-situ Reuverian.

Summary and interpretation of the cored part of the Iffezheim-Formation: According to the definition outlined above, the succession is not influenced by instable heavy minerals of the alpine Rhine. The above pollen markers show that the succession terminates well above the base of the Quaternary, i.e. in a time slice when the course of the alpine Rhine was already bound within the URG (in the western HDB proved by WEIDENFELLER & KNIPPING 2008). At the same time, maximum sedimentation rates occur on the eastern side at Heidelberg UniNord. All this requires a two-partition of the HDB, with a western basin hosting the alpine Rhine, and an eastern basin with maximum sedimentation rates. The transition between the basins is suggested to be represented by the Viernheim drilling where the Rhine sediments arrived latest.

4.5 Below 500 m

As the cored UniNord boreholes end at 500 m still within the Tiglian, the lower part of the Tiglian, the Pretiglian, and the transition into the uppermost Neogene unit i.e. the Reuverian remain uncored. In order to estimate compaction and tectonic subsidence rates, serving as accomodation space of the cored units, some basic informations on the deeper subsurface are introduced here. They rely on three available data sets: (a) the sediment log of the „Radium Sol" borehole in downtown Heidelberg, approx. 1 km south of the UniNord location; (b) the „vertical seismic profiling" (VSP) log which was recorded by the Leibniz Institute for Applied Geophysics in the UniNord 1 borehole; and (c) the sediment log of the geothermal flush borehole from Weinheim, approx. 14 km north of UniNord.

(a) The Radium Sol drilling was finished in the early 1920ies (Salomon 1927, Bartz 1951, Fezer 1998). Its overall cyclicality follows a coarse-fine-coarse pattern, with
- 0 ~ 350 m coarse and fine grained sediments;
- 350 ~ 700 m only fine grained sediments;
- 700 ~ 1000 m coarse and fine grained sediments.

(b) The VSP log was recorded as part of the geophysical downhole logging program (data recorded down to 181 m, velocity information to 160 m). It is plotted as corridor stack down to 1000 m (Buness, pers. comm.). We do not interpret individual reflections but evaluate their frequency. There are many strong reflections in the upper part and again several though weaker reflections in the lower part, but almost none in a middle interval from 350 down to 700 m. This is unlikely in a succession of alternating coarse and fine sediments. We conclude fine sediment dominance down to 770 m.

(c) Also at Weinheim where two boreholes were flushed down to ~ 1000 m, a long interval of fine sediment domination has been detected down to 700 m.

We conclude that, at UniNord, the high ratio of fine sediment will continue or even increase in the interval 500 to 700 m, estimated 50 % of fines or more. It will then again decrease in the 700 to 1000 m interval where coarse and fine sediments alternate. Assuming constant sedimentation rates as derived below, the transition from the Neogene Reuverian unit to the Pleistocene Pre-Tiglian stage is now predicted close to or below 600 m.

5 The Heidelberg Boreholes – Synopsis, Conclusions, Outlook

5.1 Sedimentation rates, Accommodation Space and Subsidence

The patterns of Lithostratigraphy and Chronostratigraphy are compared in Table 1. Basically the lithostratigraphic boundaries are controlled by tectonics whereas Chronostratigraphy refers to climate. They are identical where the lithostratigraphy is based on the local lithofacies patterns, i.e. the boundaries of the Ladenburg-Sfm and the Mannheim-Fm.
Table 1 also includes „absolute" ages (STD 2002, Ogg, Ogg & Gradstein 2008). They serve as a geochronologic frame to estimate average sedimentation rates for the units (Tab. 2, Fig. 6). They are, as yet, uncorrected, but may be used to calculate the non-tectonic i.e. compaction part of the subsidence.

5.2 Input and uplift

The local aspect: The relatively rapid increase of sediment thickness during Eburonian time is associated with coarse, clastic deposits. Clastic fragments are derived from Triassic sedimentary rocks and the Heidelberg granite and associated crystalline rocks of the Variscan basement. This sediment composition is interpreted to reflect the synchronous uplift of the adjacent rift shoulder and the initiation or reactivation of faults in the Heidelberg town area, which trend both subparallel with and at a high angle to the major, eastern rift bounding fault. Activities at these faults led to the exposition of the crystal-

Table 1: Lithostratigraphy and Chronostratigraphy of the sediment succession of the borehole Heidelberg UniNord. The lithostratigraphic boundaries are controlled by tectonics (cf. Tab. 2); the chronostratigraphic stages refer to the alpine and north European glaciations and to the pollen-based biostratigraphy of NW-Europe. Sediment thicknesses are uncorrected.

Tab. 1: Lithostratigraphie und Chronostratigraphie der Sedimentfolge aus der Bohrung Heidelberg UniNord. Die lithostratigraphischen Grenzen sind tektonisch gesteuert (vgl. Tab. 2); die chronostratigraphischen Stufen beziehen sich auf die alpinen und nordeuropäischen Vergletscherungen und auf die pollenanalytisch begründete Biostratigraphie NW-Europas. Sedimentmächtigkeiten sind nicht korrigiert.

Lithostratigraphy				*Chronostratigraphy*		
Formation	*Sub-formation*	*Interval thickness*		*original Interval thickness*	*Pollen*	
Mannheim-Fm 0 – 56 m	Neckar fan	12 m		56 m		Holocene; Würm/Weichsel; Riss/Saale; Hoßkirch/Elster
	fluvial gravel	44 m				
	Diamicton and fines, fossil soil					
	fluvial gravel, diamicton					
Kurpfalz-Fm 56 – 299 m	Ladenburg-Sfm (mass flow, fluvial, lacustrine)	70 m		70 m		Cromerian
	(K3) two fluvial pulses 126 – 237 m	111 m		44 m	*Pinus*, *Picea* *Tsuga*	Bavelian 126 – 170 m
				40 m	*Tsuga*, *Pterocarya*	Waalian 170 – 210 m
				130 m	Coniferous forest 210 – 250 m	Eburonian 210 – 340 m
	(K2) lacustrine 237 – 263 m	26 m			No pollen	
	(K1) mass flow, fluvial, lacustrine, 263 – 299 m	36 m				
Iffezheim-Fm 299 – 500 m	(I6) lacustrine fines and Sand 299 – 316 m	17 m			Open forest at 312 m	
	(I5) fluvial sand 316 – 382 m	66 m			Coniferous forest at 316 m	
	(I4) fluvial overbank 382 – 411 m	29 m		160 m	early Pleistocene pollen spectra with *Fagus* and Tertiary taxa increasing downward	Tiglian 340 – >500 m
	(I3) fluvial sand 411 – 451 m	40 m				
	(I2) fluvial overbank 451 – 467 m	16 m				
	(I1) fluvial sand 467 – 500 m	33 m				
Not drilled: Iffezheim-Fm 500 > 700 m	sand and fines	?		*estimated 20 m*		
	sand and fines	?		*estimated 80 m*		Praetiglian
	mainly fines	?		*estimated > 100 m*		Reuverian

Table 2: Average sedimentation rates of the chronostratigraphic units, according to uncorrected thickness and age data of Table 1. Cf. Fig. 6.
Control of the subsidence: We suggest tectonic control only if the sedimentary environment relies on tectonic subsidence. This is, presently, only the case in the lacustrine intervals covering small areas in the Heidelberg deep (Eburonian, Cromerian). In all other cases we suggest that considerable parts of the accomodation space come up from compaction of underlying fine sediments. This will be considered in future studies, including correction of the sedimentation rates. - The discussion of the potential tectonic control of the input remains unaffected.

Tab. 2: Durchschnittliche Sedimentationsraten für die chronostratigraphischen Einheiten, unter Verwendung der unkorrigierten Sedimentmächtigkeiten und Altersdaten aus Tab. 1. Vgl. Abb. 6.
Steuerung der Subsidenz: Wir diskutieren eine tektonische Steuerung nur dann, wenn das Ablagerungsmilieu nicht anders hergeleitet werden kann. Das ist bisher nur in den lakustrinen Abschnitten der Fall, die nur kleinräumlich im Heidelberger Loch nachgewiesen sind (Eburon, Cromer). Ansonsten gehen wir derzeit davon aus, dass ein erheblicher Teil des Akkomodationsraums auch durch Kompaktion der Feinsedimente aus dem Liegenden herzuleiten ist. Bei der weiteren Bearbeitung sind die Sedimentationsraten entsprechend nach oben zu korrigieren. - Die potentielle tektonische Steuerung des Inputs bleibt unberührt.

Chrono-stratigraphy	*Sediment Thickness*	*Amount of fine sediments*	*Duration*	*Sedimentation rates (uncorrected)*		*Suggested major control of Subsidence*
				Meter/ka	*mm/a*	
Würm, Riss, Hosskirch	56 m	< 5 m	450 ka	56 / 450	0.1	*Non-tectonic*
Cromerian	70 m	40 m	350 ka	70 / 350	0.2	*Tectonic*
Bavelian	44 m	5 m	600 ka	44 / 600	< 0.1	*Non-tectonic*
Waalian	40 m	15 m	200 ka	40 / 200	0.2	*non-tectonic*
Eburonian	130 m	70 m	200 ka	130 / 200	0.7	*Tectonic*
Tiglian	160 m (180 m)	60 m	600 ka	180 / 600	0.3	*non-tectonic*

line rocks, fragments of which are now found in the basin sequence. The subsequent period is characterized by thin sediments and may be related to a peneplanation observed at the rift shoulder. The ultimate stage, represented by the Mannheim Formation, with a more rapid increase in sediment thickness is lasting until the present and associated with renewed uplift of the rift shoulders. This uplift is accompanied by a dissection of the peneplain surface, caused by the reactivation of pre-existing faults.

The regional aspect: The first onset of alpine sedimentation in the HDB, as identified in the Ludwigshafen succession (Weidenfeller & Knipping 2008) reflects the redirection of the alpine Rhine into the URG, prior to the Pliocene-Pleistocene transition at ~ 2.6 Ma (e.g. Hoselmann 2008). The redirection happens in the Mulhouse area where the first signal of alpine heavy minerals in the URG fill goes along with an abrupt coarsening of the lithofacies of alpine and local sediment. This composition has been interpreted as to reflect the starting uplift of parts of the southern Black Forest (Ellwanger 2003), probably related to the latest folding in front of the Jura mountains (Giamboni et al. 2004).

Two subsequent uplift markers are identified in the UniNord succession. They are related to the coarse input at the basal Kurpfalz-Formation (Eburonian, ~ 1.7 Ma) and to the coarse input

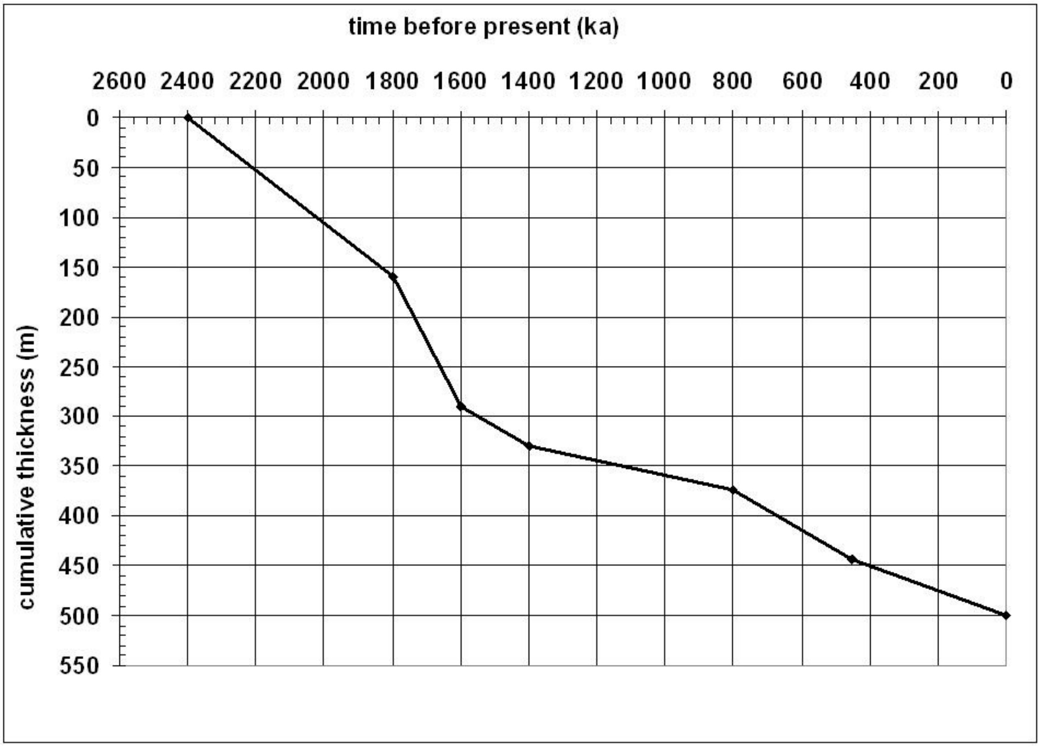

Fig. 6: Net accumulation of the sedimentary sequence through time of the Heidelberg UniNord borehole, using thickness and age data of Table 2.

Abb. 6: Sedimentmächtigkeiten der Bohrung Heidelberg UniNord gegen stratigraphische Zeitskala, unter Verwendung unkorrigierter Mächtigkeiten und Alter aus Tab. 2.

at the basal Mannheim-Formation (post-Cromerian, ~ 0.5 Ma). Both reflect uplift periods of the Odenwald. The post-Cromerian uplift is contemporaneous with the main uplift of the Rhenish Massif (cf. various studies of the lower main terrace e.g. HOSELMANN 1994).

All this leads to a scenario of Quaternary uplift = input events in cycles of ~1 Ma, proceeding from south to north:

- ~0.5 Ma Rhenish Massif plus Odenwald (?plus Black Forest);
- ~1.7 Ma Odenwald (?plus Black Forest);
- ~2.6 Ma southern Black Forest.

Each uplift event potentially provides sediment supply which will more easily be activated if the mechanical erosion is facilitated by climate changes (e.g. VANDENBERGHE 1993, 1995, BUSSCHERS 2007). In case of the middle input event the Tiglian to Eburonian transition is proved to occur well below the coarse input is recorded. This supports the above scenario. The other events lack of chronostratigraphic data.

5.3 Outlook

The descriptions, basic data and correlative patterns presented here are all focused upon the specific situation of the Heidelberg deep i.e. the cores of the borehole of the UniNord location in Heidelberg. In the interpretative steps to follow, the controlling parameters of sedimentation will have to be more thoroughly identified, e.g. are increasing a/s-ratios due to tectonic subsidence or to compaction within the basin, or due to uplift around the basin. This can only be accomplished if the entire HDB is regarded. Additional boreholes (e.g. Haimberger, Hoppe & Schäfer 2005, Wirsing et al. 2007, Hoselmann 2008, Hunze & Wonik 2008, Simon 2008, Weidenfeller & Knipping 2008) as well as seismic and logging data (Buness, Gabriel & Ellwanger 2008) will have to be included

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The Heidelberg Basin drilling project: Geophysical pre-site surveys

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Abstract: Currently, the Heidelberg Basin is under investigation by new cored research boreholes to enhance the understanding concerning the control on Pliocene and Quaternary sedimentation by (neo)tectonics and climate. The Heidelberg Basin is expected to serve as a key location for an improved correlation of parameters that characterise the climate evolution in North Europe and the Alpine region. The recovery of sediment successions of high temporal resolution that are complete with respect to the deposition of Pleistocene glacials and interglacials in superposition is of special importance. Prior to the new research boreholes in Viernheim and Heidelberg geophysical pre-site surveys were performed to identify borehole locations that best achieve these requirements. In the area of the Heidelberg Basin the strongest negative gravity anomaly of the entire Upper Rhine Graben is observed (apart from the Alps), hinting at anomalously thick sediment deposits. However, especially reflection seismic profiles contributed significantly to the decision about the borehole locations. In the city of Heidelberg for the first time, the depocentre of the Heidelberg Basin, as indicated by additional subsidence compared to its surroundings, was mapped. In this area, sediments dip towards the eastern margin of the Upper Rhine Graben. This is interpreted to represent a rollover structure related to the maximum subsidence of the Upper Rhine Graben in this region. At the Viernheim borehole location the seismic survey revealed several faults. Although these faults are mainly restricted to depths greater than 225 m, the borehole location was finally adjusted with respect to this information.

[Das Bohrprojekt Heidelberger Becken: Geophysikalische Voruntersuchungen]

Kurzfassung: Das Heidelberger Becken wird aktuell durch neue Kernbohrungen untersucht, um das Wissen hinsichtlich der Steuerung der pliozänen und quartären Sedimentation durch Klima und (Neo)Tektonik zu erweitern. Es wird erwartet, dass das Heidelberger Becken eine Schlüsselstelle für eine verbesserte Korrelation von Parametern darstellt, welche die Klimaentwicklung in Nordeuropa und im alpinen Raum charakterisieren. Besondere Bedeutung hat daher die Gewinnung von Sedimentsukzessionen hoher zeitlicher Auflösung, die im Hinblick auf die Ablagerung kalt- und warmzeitlicher pleistozäner Sedimente in Superposition möglichst vollständig sind. Im Vorfeld der neuen Kernbohrungen bei Viernheim und Heidelberg wurden geophysikalische Vorerkundungen durchgeführt, um Bohrlokationen zu identifizieren, die diesen Ansprüchen am besten genügen. Im Bereich Heidelberg wird die größte negative Schwereanomalie des gesamten Oberrheingrabens beobachtet (mit Ausnahme der Alpen), was auf ungewöhnlich mächtige Sedimentablagerungen hindeutet. Aber insbesondere reflexionsseismische Messungen haben zur Auswahl der Bohrpunkte beigetragen. Im Stadtbereich von Heidelberg ist zum ersten Mal das Depozentrum des Heidelberger Beckens kartiert worden, abgebildet durch eine zusätzliche Absenkung gegenüber der Umgebung. In diesem Gebiet fallen die Sedimente zum östlichen Grabenrand hin ein. Dies wird als 'Rollover' Struktur interpretiert, die in Verbindung mit der maximalen Subsidenz des Oberrheingrabens in diesem Bereich steht. An der Bohrlokation Viernheim konnten durch die Seis-

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mik zahlreiche Störungen abgebildet werden. Obwohl diese im Wesentlichen auf Tiefenbereiche größer 225 m beschränkt sind, wurde der Bohransatzpunkt schließlich aufgrund dieser Informationen gewählt.

Keywords: Heidelberg Basin, depocentre, research borehole, reflection seismic, gravity

1 Introduction

The Heidelberg Basin is located in the eastern part of the Northern Upper Rhine Graben (URG; Fig. 1), bordered by the dominating master fault of the URG to the east. The boundary fault is assumed to extend deep into the crust, by 15 - 24 km according to MAUTHE,

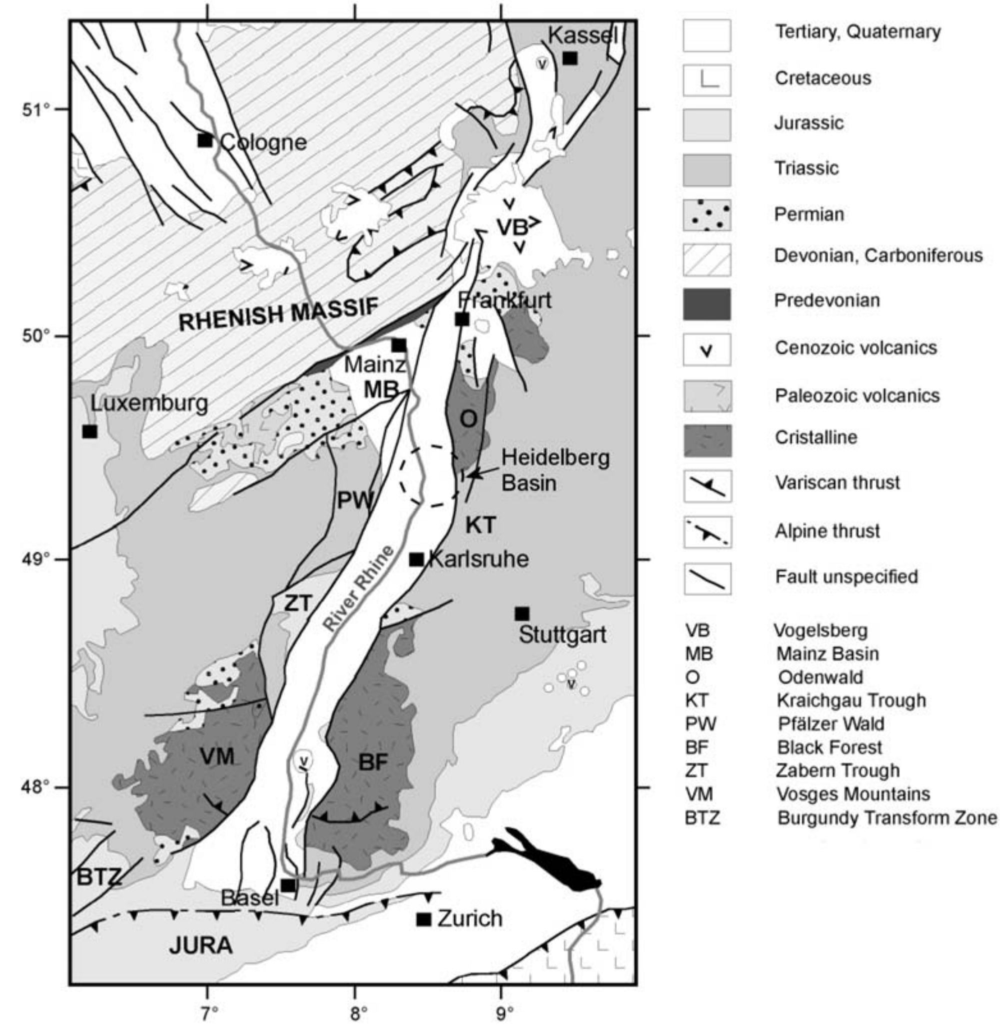

Fig. 1:Tectonic sketch map of the Upper Rhine Graben and its surroundings (after PETERS 2007). The approximate position of the Heidelberg Basin is marked by a dashed line.

Abb. 1: Tektonische Skizze des Oberrheingrabens und seiner Umgebung (nach PETERS 2007). Die Lage des Heidelberger Beckens wird durch einen gestrichelten Kreis angedeutet.

Brink & Burri (1993). The sedimentary fill of the URG is characterised by synthetic and antithetic faults which strike parallel or subparallel to this boundary fault. The area of the Heidelberg Basin was subjected to continuous and strong subsidence since late Oligocene (Schumacher 2002). Up to 1500 m sediments were deposited in early Miocene alone (comprising *Cerethia*, *Corbicula*, and *Hydrobia* beds). The thickest succession of Quaternary sediments can be found here (up to 350 m according to Bartz 1974; Fig. 2, top).

The Heidelberg Basin constitutes therefore the most complete sediment archive of the whole URG. Sediments of different geosystems interfere with each other: the local system of the Neckar River (Odenwald), the regional Upper Rhine Graben-Highlands (Black Forest, Vosges) system, and the supra-regional Alps-Upper Rhine Graben system. Especially the distal deposits of the system Alps – Upper Rhine Graben are supposed to contain information about both the alpine and north European climate history, which can not be observed elsewhere (e.g. Ellwanger et al. 2005). The term Heidelberg Basin stands for the Miocene to Quaternary depocentre of the northern URG with an extent of some tens of km. The term 'Heidelberger Loch', sometimes also found in literature, was introduced by Salomon (1927) and denotes the locally, very delimited centre of subsidence around the city of Heidelberg.

The exploration of this sediment archive is the aim of two new research boreholes sponsored by the Leibniz Institute of Applied Geophysics (LIAG – former Leibniz Institute for Applied Geosciences, GGA-Institut) and the geological surveys of Baden-Württemberg (LGRB) and Hessen (HLUG) (Fig. 2, bottom). One of the boreholes was drilled exactly in the depocentre of the basin, close to the outlet of the Neckar River, from the Odenwald to the plain of the Upper Rhine Graben ('Heidelberg UniNord', Ellwanger et al. 2008). The other one was drilled in the geographic centre of the Heidelberg Basin about 17 km to the northwest, near the city of Viernheim (Hoselmann 2008). These two locations are complemented by two boreholes in Ludwigshafen that were drilled on the 'Parkinsel' island on the western margin of the basin (Fig. 2, bottom; Weidenfeller & Knipping 2008).

Prior to drilling these boreholes, a number of seismic profiles were carried out to facilitate a profound drilling design (Fig. 2; bottom). This included an estimation of depths for the geological targets, i.e. Pliocene and Pleistocene strata as well as the detection of possible fault zones. The latter point was important because the boreholes were to serve as a stratigraphic reference for the Quaternary sediment succession. Furthermore, high resolution seismic profiles in general are able to reveal tectonic and sedimentological events caused by the continued subsidence of the basin.

This article presents the results of the pre-site surveys. However, at the present stage, as there is not even a consistent and homogenous interpretation of all available borehole data, it is not possible to make conclusions about the basin dynamics (e.g. a seismostratigraphic interpretation). A more exhaustive analysis of the data could be done in the framework of a project, which was proposed to the German Research Foundation and is currently under evaluation.

2 Geological setting and nomenclature

Knowledge about the deeper subsurface of the URG is based mainly on seismic profiling and evaluation of boreholes of the oil and gas industry, which was quite intensively done in this area. According to Mauthe, Brink & Burri (1993), about 5000 km seismic lines were recorded between 1970 and 1992. An extensive presentation of these activities is not possible due to the lack of corresponding publications. However, isobath maps derived from these data were published, e.g. for the Tertiary by Doebl & Olbrecht (1974) or for the Quaternary by Bartz (1974).

Two deep-reaching reflection seismic profiles running across the southern and northern URG were carried out in 1988 in the framework of the DEKORP-ECORS Project (Brun & Gutscher 1992). The northern profile crosses the URG

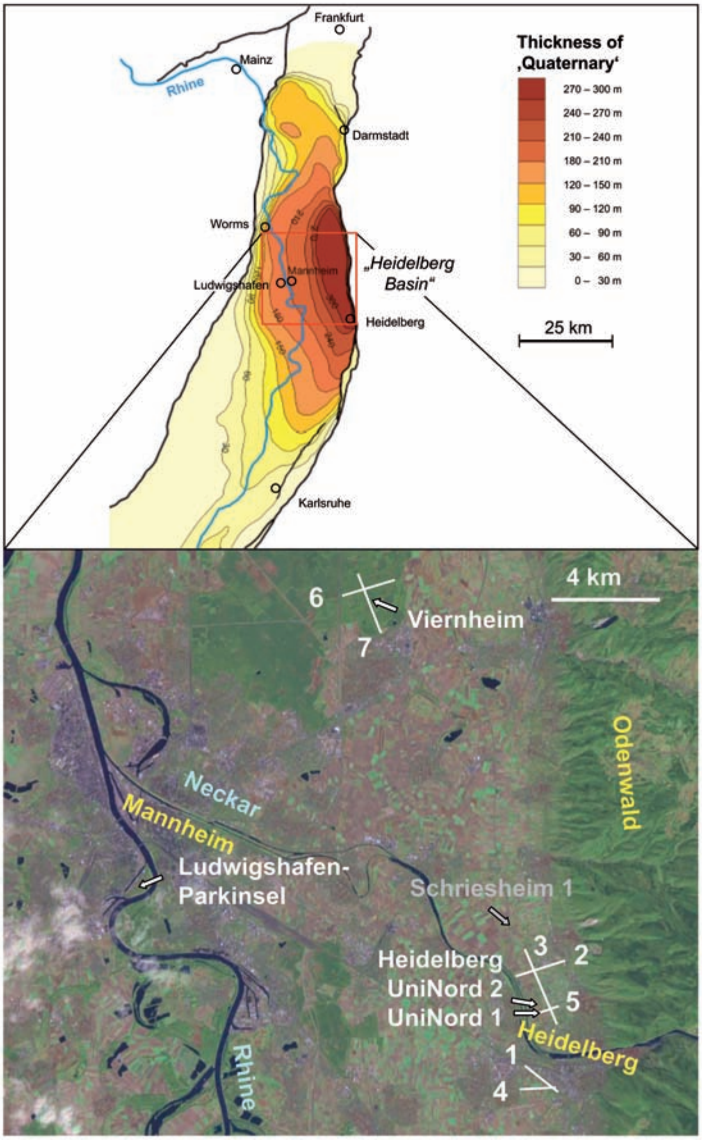

Fig. 2: *Top*: Thickness of 'Quaternary' in the northern part of the Upper Rhine Graben, adopted from Bartz (1974, updated by Haimberger, Hoppe & Schäfer 2005). *Bottom*: Satellite view of the Heidelberg area (created with NASA World Wind, Vers. 1.3.2). White arrows: research boreholes Heidelberg UniNord (two boreholes in 2006 and 2008), Viernheim (2006), and Ludwigshafen-Parkinsel (two boreholes in 2002 and 2006); grey arrow: hydrocarbon well 'Schriesheim 1'. White lines: reflection seismic profiles 1-7 that are discussed in this paper.

Abb. 2: *Oben*: Mächtigkeiten des 'Quartär' im nördlichen Teil des Oberrheingrabens nach Bartz (1974, aktualisiert durch Haimberger, Hoppe & Schäfer 2005).
Unten: Satellitenaufnahme des Heidelberger Raums (erstellt mit NASA World Wind, Vers. 1.3.2). Weiße Pfeile: Forschungsbohrungen Heidelberg UniNord (zwei Bohrungen in 2006 und 2008), Viernheim (2006) und Ludwigshafen-Parkinsel (zwei Bohrungen in 2002 und 2006); grauer Pfeil: Kohlenwasserstoffbohrung 'Schriesheim 1'. Weiße Linien: reflexionsseismische Profile 1-7, die in diesem Artikel diskutiert werden.

about 20 km north of Heidelberg. The varying reflector signature of the lower crust images the asymmetric structure of the URG. The largest Tertiary sediment thickness of 3400 m is observed close to the eastern rim of the graben, it reduces stepwise to 300 m below the western border. However, depths corresponding to the Quaternary, the Pliocene, and down to the middle Miocene units are poorly resolved.

The interaction between tectonic and sedimentation in the northern URG was investigated by Derer by means of sequence stratigraphy (Derer 2003, Derer et al. 2003, Derer, Schumacher & Schäfer 2005), who found the area to be divided into two halfgrabens with opposing tilt directions by a transfer zone. The study was based on seismic profiles and geophysical borehole measurements made by the oil and gas industry. Seismic facies were assigned to several lithostratigraphic units from Eocene to the upper Miocene.

About 190 km of industrial seismic lines where shot between 1981 und 1993 in the Heidelberg Basin. However, these lines do not extend to the depocentre of the Heidelberg Basin ('Heidelberger Loch'). Furthermore, only little information about the structure of Plio-Pleistocene sediments can be derived from the hydrocarbon seismic lines, because these focused only on storage or sealing horizons, and hence deep structures. The existing gap in the reflection seismic data, near to the city of Heidelberg, can be partly filled by information from boreholes related to hydrogeological investigations. In the Heidelberg area two flush boreholes are available that reveal large thickness of Quaternary sediments: the 350 m deep Entensee borehole from 1973 (Conrads & Schneider 1977), about 1 km north, and the 1022 m deep Radium-Sol Therme borehole from 1918 (Salomon 1927), about 1 km south of the new borehole Heidelberg UniNord 1 (Fig. 3).

Interpretation of these two boreholes is controversially discussed. The main problem here are the confusing definitions and applications of the terms Quaternary and Pliocene (and some other stratigraphic terms) in publications, reports and archives related to the URG. The most frequently applied 'traditional' definition relates 'Quaternary' to the onset of alpine sediments, i.e. to a change in sediment provenance. 'Pliocene' sediments come from local sediment sources, e.g. Black Forest, Vosges, and Odenwald; 'Quaternary' sediments include or correlate with sediments of alpine origin. This change of provenance is, of course, a matter of lithostratigraphy, although chronostratigraphic terms are used.

This different use of the term 'Quaternary' is illustrated by the controversial interpretations of the Radium-Sol Therme borehole by Salomon (1927), Bartz (1951) and Fezer (1997). Salomon and Bartz suggest depths of '382 m' and 'almost 400 m', both referring to the lithostratigraphic version of 'Quaternary'; Fezer suggests a depth of 650 m which is based upon a calculation of sedimentation rates i.e. he applies the term Quaternary in its proper chronostratigraphic sense.

The aim of this paper is not to solve problems of stratigraphic nomenclature but report seismic and gravimetric activities prior to the new drilling activities. Our references are the old data (publications, reports, and archive data) which are, at this state, not re-interpreted but used as they are. Stratigraphic terms are set in quotation marks where we feel the authors use the lithostratigraphic version (e.g. 'Quaternary'), and without quotation marks when used as chronostratigraphic term (e.g. Quaternary).

A reflection seismic profile that focused especially on the Quaternary deposits was published by Haimberger, Hoppe & Schäfer (2005). This river seismic profile - recorded along the Rhine River between Mainz and Mannheim, and parts of the Neckar River over a length of 150 km in total - revealed high-resolution information which was able to define the base of 'Pleistocene' sediments mainly north of Mannheim. Maximum thickness of 'Pleistocene' was found in the area of Mannheim and confirmed the map published by Bartz (1974; Fig. 2). This map images an increase of 'Pleistocene' sediment thickness towards the eastern boundary fault of the Upper Rhine Graben, where it amounts to more than 350 m.

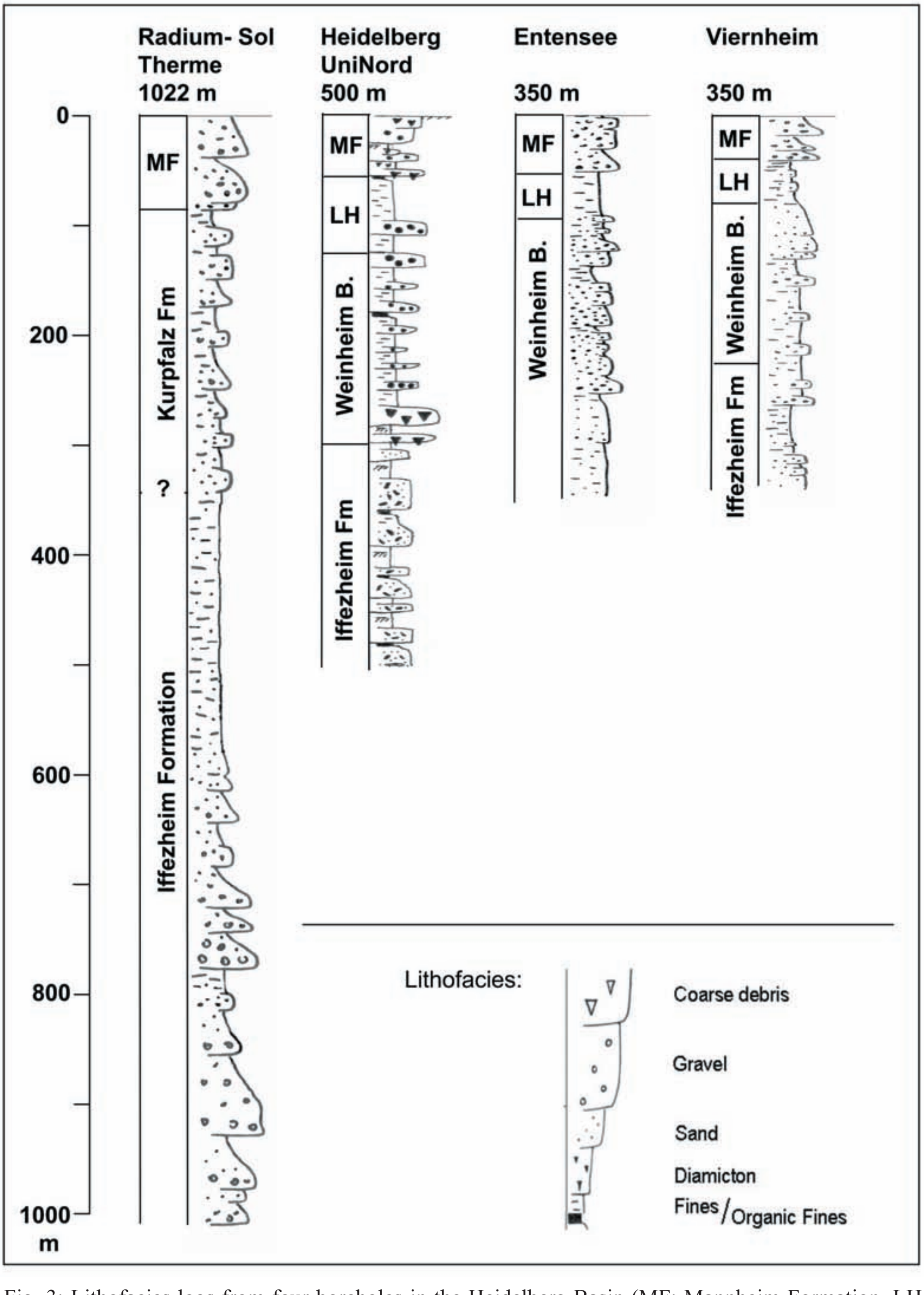

Fig. 3: Lithofacies logs from four boreholes in the Heidelberg Basin (MF: Mannheim-Formation, LH Ladenburg-Horizon).

Abb. 3: Lithofazieslogs von vier Bohrungen im Heidelberger Becken (MF Mannheim-Formation, LH Ladenburg-Horizont).

Table 1: Different classifications of Plio-Pleistocene sediments, as used in the Upper Rhine Graben. The terms 'Altquartär' and 'Pliocene' (senso Bartz) are defined by lithofacies, rather than a strict geochronological classification.

Tab. 1: Gegenüberstellung verschiedener Einteilungen der plio-/pleistozänen Sedimente für den Oberrheingraben. Die Begriffe 'Altquartär' und 'Pliozän' (nach Bartz) definieren eher Sedimenttypen, denn eine strikte geochronologische Einordnung.

<table>
<tr><th colspan="2">Baden-Württemberg
Symbolschlüssel Geologie Baden-Württemberg</th><th>Rheinland-Pfalz
Weidenfeller & Kärcher 2008
Weidenfeller & Knipping 2008</th><th>Hessen</th><th rowspan="2">Bartz 1982</th></tr>
<tr><td colspan="2"></td><td></td><td>Aeolian sand (Pleistocene to Holocene)</td></tr>
<tr><td colspan="2">Mannheim-Formation</td><td>Upper gravel layer (OKL)</td><td>Sand-gravel layers
Neckar dominated, less alpine</td><td>Oberes Kieslager (OKL)
contains coarse material (alpine and local)</td></tr>
<tr><td rowspan="4">Kurpfalz-Formation</td><td>Ladenburg Horizon</td><td>Upper interlayer (OZH)</td><td>Interlayer
predominant fine-clastic sediments</td><td>Obere Zwischenschicht (OZ)
only fine material</td></tr>
<tr><td rowspan="3">Weinheim Beds</td><td>Middle sand-gravel layer</td><td rowspan="3">Alternation of
sand-(gravel) layers frequently in "Rhenish Facies" and
fine-clastic interlayers
Rhine (alpine) material, less Neckar</td><td>Mittleres Kieslager (MKL)
contains coarse material</td></tr>
<tr><td>Lower interlayer (UZH)</td><td>Untere Zwischenschicht (UZ)
only fine material</td></tr>
<tr><td>Lower sand-silt layer</td><td>Unteres Kieslager (UKL)
contains coarse material
'Altquartär 1 and 2' (AQ1 and AQ2)
transition unit, contains the lowermost alpine material</td></tr>
<tr><td colspan="5">major change of provenance</td></tr>
<tr><td colspan="2">Iffezheim-Formation</td><td>Clay-silt-sand-layer</td><td>Clay-silt- and sand-layers
material of local provenance</td><td>'Pliocene I-III'
material of local provenance</td></tr>
</table>

The interpretation of the river seismic data revealed well the alternating sequence of coarse-grained layers (aquifers, so called 'Kieslager') and fine-grained layers (aquitards, so called 'Zwischenhorizonte') typical of the Heidelberg Basin. This hydrostratigraphic classification (Table 1) is often used in the northern part of the Upper Rhine Graben due to a lack of geochronological data concerning Pliocene and Pleistocene strata. It is based on a macroscopic description of the sediments, their colours and carbonate content, and as complementary information on gamma logs, where available. The hydrostratigraphy was broadly introduced by Bartz (1982). It is presently much used in hydrogeology (HGK 1999) and was last updated by Weidenfeller & Kärcher (2008). On a larger scale it distinguishes between three coarse-grained layers separated by two fine-grained layers, which are regionally distributed. In the system after Bartz (1982) this alternating succession is separated from the underlying provenance change by another unit called 'Altquartär' ('Early Quaternary'). This term again is used as description of a sediment type rather than a stringent chronostratigraphic classification. In more recent publications and reports, the lowest coarse-grained bed is defined as Early Quaternary (Weidenfeller & Kärcher 2008). The thickness of each layer is quite variable in a lateral direction. Locally, additional fine- or coarse-grained layers of smaller extent can be intercalated. The occurrence of fine-grained sediments was traditionally related to interglacial periods, and the occurrence of coarse-grained layers to glacial periods (Bartz 1982).

One of the aims of this drilling project is to correlate the before mentioned hydrostratigra-

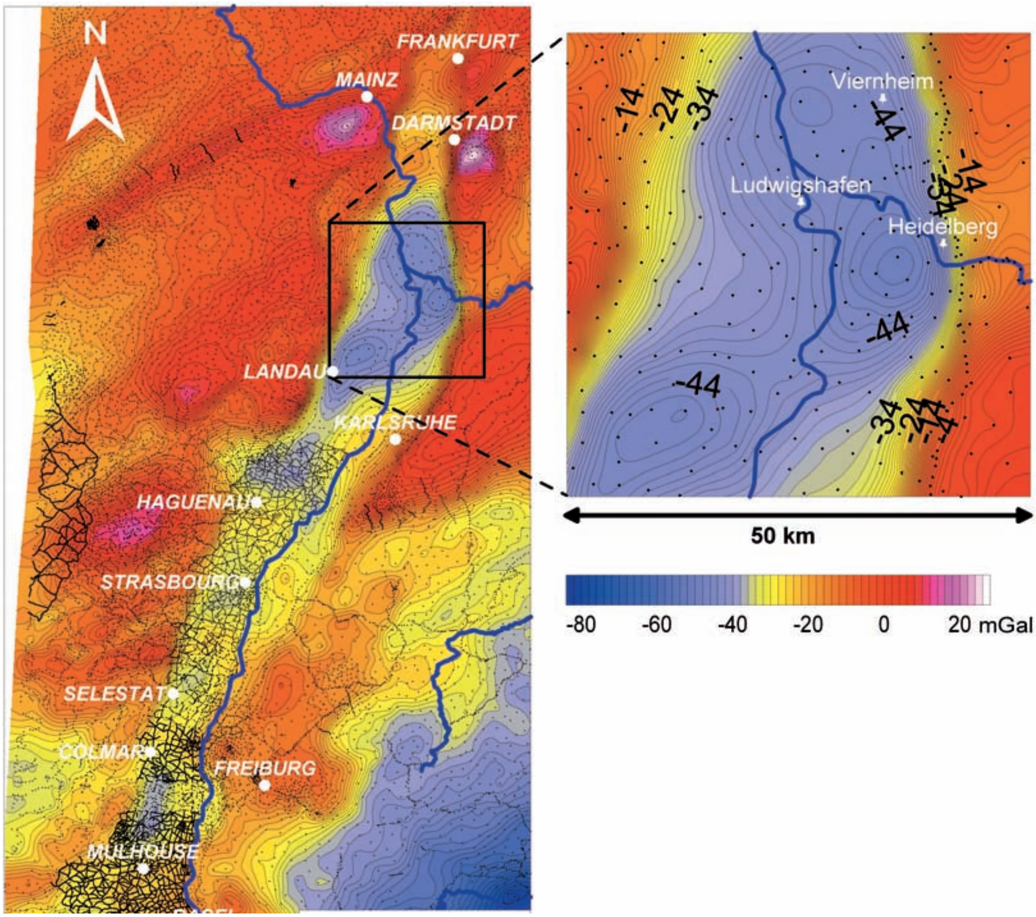

Fig. 4: Bouguer map of the entire Upper Rhine Graben (after Rotstein et al. 2006) and the Heidelberg area in more detail, with the three research borehole locations Ludwigshafen-Parkinsel, Viernheim, and Heidelberg. Contour intervals: 2 mGal (regional map) and 1 mGal (local map); black dots: gravity stations.

Abb. 4: Bouguer-Karte des gesamten Oberrheingrabens (nach Rotstein et al. 2006) und des Heidelberger Raums im Detail mit den drei Lokationen der Forschungsbohrungen Ludwigshafen-Parkinsel, Viernheim und Heidelberg. Isolinienabstand 2 mGal (regionale Karte) und 1 mGal (lokale Karte); schwarze Punkte: gravimetrische Messpunkte.

phy with the lithostratigraphy of the southern part of the Upper Rhine Graben (Symbolschlüssel Geologie Baden-Württemberg). The upper gravel layer can be quite well correlated with the Mannheim Formation, and the upper interlayer (fine-grained layer) with the Ladenburg Horizon. The succession of the middle sand-gravel layer and lower sand-silt layer and the interlayer in between is only roughly equivalent to the Weinheim Beds (Table 1).

3 Gravimetry

Generally, gravity anomaly data is expected to reflect a first-order pattern of the shape of the Heidelberg Basin, especially varying thickness of (unconsolidated) Pliocene/Pleistocene sediments. The mean density of Plio-Pleistocene sediments should be reduced compared to Tertiary or even older and more compacted sediments. Therefore the anomalous thick sedimentary fill of the Heidelberg Basin should cause a

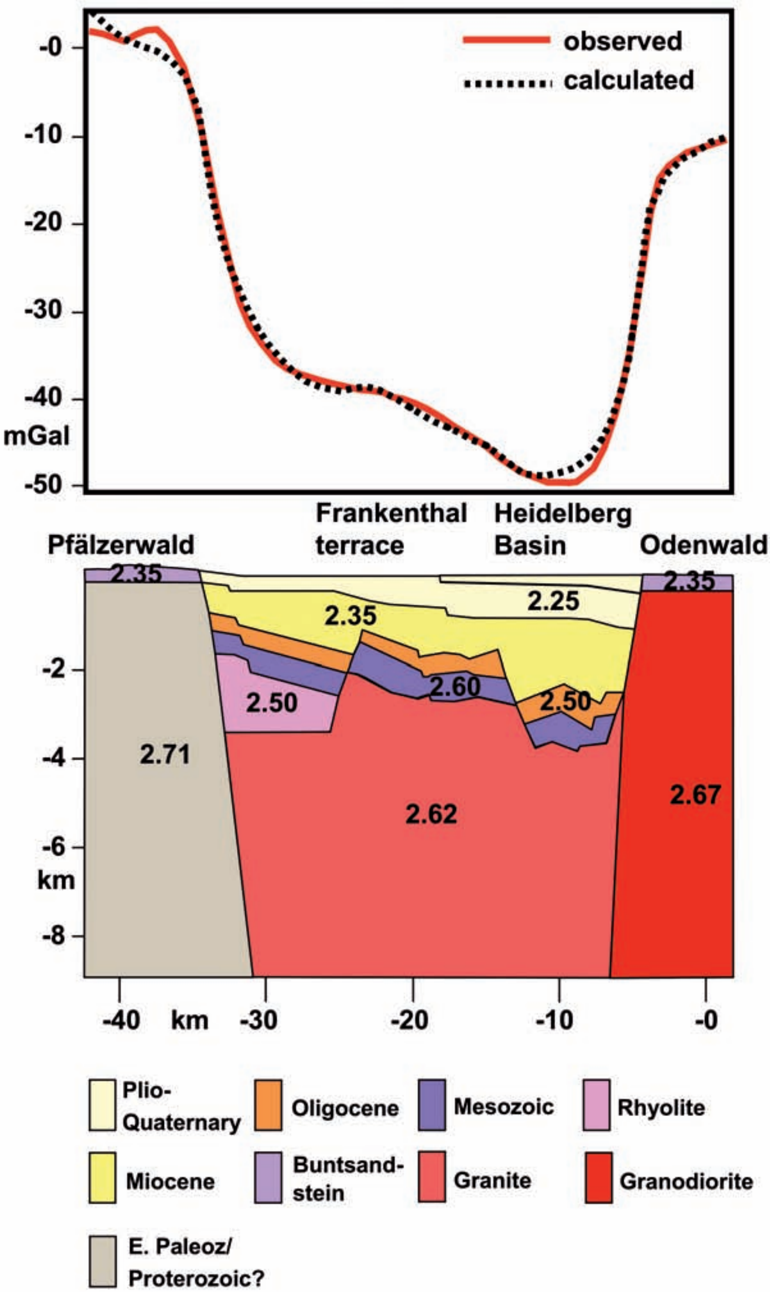

Fig. 5: 2-D gravity profile across the Rhine Graben in the Heidelberg area. Although the regional gravity field correlates well with sediment thickness, additional density contrasts in the basement are required to explain the observed anomalies in the western part.

Abb. 5: Gravimetrisches 2-D Profil über den Rheingraben im Raum Heidelberg. Wenngleich das regionale Schwerefeld gut mit den Sedimentmächtigkeiten korreliert, müssen Dichtekontraste im Basement angenommen werden, um die beobachteten Anomalien des westlichsten Profilabschnitts zu erklären.

negative gravity anomaly that can be related to the the extent of the basin and its depth. But in fact the situation is more complicated.

Gravity data

Gravity data for the Upper Rhine Graben is available from several sources. Rotstein et al. (2006) have compiled the most recent Bouguer gravity map of the Upper Rhine Graben comprising all the available data from France and Germany (Fig. 4; regional map). This map is based on about 33.000 Bouguer gravity values. About one third of the data was provided by the Leibniz Institute for Applied Geophysics covering the German part of the Rhine Graben. This dataset consists of data available from the Geophysikalische Reichsaufnahme, but also some local surveys. The French data is mainly based on two data sources, which are themselves compilations of numerous surveys. The first dataset – about fifty percent of the French data - was provided by the Bureau de Recherches Géologiques et Minières, the second one by Mines de Potasse d'Alsace. A complete Bouguer anomaly was recalculated for the entire new dataset, using a density of 2670 kg/m^3 and considering newly-calculated terrain reductions. The distribution of the gravity stations is strongly inhomogeneous; their spatial coverage varies significantly from about 0,25 stations/km^2 in some parts of the Vosges and Black Forest and 40 stations/km^2 in some parts of the graben itself. Note, the complete Bouguer map is based on a calculated grid of 1 km.

The area of the Heidelberg Basin (Fig. 4; local map) is characterised by the strongest gravity anomaly of the entire Upper Rhine Graben (apart from the most southern part where the regional trend is strongly affected by the Alps). It is in the order of -40 to -50 mGal, with the absolute minimum close to the outlet of the Neckar River, from the Odenwald in the plain of the Upper Rhine Graben (Fig. 4).

Preliminary Interpretation

When interpreting the anomaly apparently related to the sediment fill of the Heidelberg Basin some general knowledge regarding the source of gravity anomalies in the Upper Rhine Graben has to be considered. Rotstein et al. (2006) performed some two-dimensional calculations along profiles approximately perpendicular to the strike of the graben. Although these profiles were restricted to the southern part of the graben and a two-dimensional approach is not suitable to investigate the complex graben geology in great detail, their general result showed, that the gravity anomalies are not only caused by the sediment fill of the graben, but that they are also strongly affected by density inhomogeneities in the crystalline basement. One of the profiles south of Karlsruhe revealed increasing sediment thicknesses from west to east accompanied by increasing Bouguer gravity values – the structure of the sediments was well constrained by reflection seismic data and drilling information. Therefore, for this profile the gravity effect of the sediments must be overcompensated by density contrasts in the basement.

Density of the basement must be assumed to be of high lateral variation as that of rocks of the adjacent graben shoulders is. Therefore, some impact on the Bouguer anomalies observed in the area of the Heidelberg Basin must also be assumed. A preliminary 2-D profile which crosses the Rhine Graben close to Heidelberg is shown in Fig. 5. Although the structural resolution of the sediments is rather low, the necessity to introduce at least lateral density contrasts at the western and eastern boundary faults and within the most western part of the basement is obvious.

Nevertheless, the sediments of the Heidelberg Basin will undoubtedly contribute to the negative gravity anomalies observed in this region. Confirming the map of 'Quaternary' thickness in the Upper Rhine Graben published by Bartz (1974), the new reflection seismic profiles recorded in the framework of the pre-site surveys reveal anomalously thick Neogene sediments. From the downhole logging experiments conducted in the Heidelberg Drilling Project, low densities between 2000 kg/m^3 and 2300 kg/m^3 can be estimated for the Pleistocene sediments (Hunze & Wonik 2008), whereas Tertiary sedi-

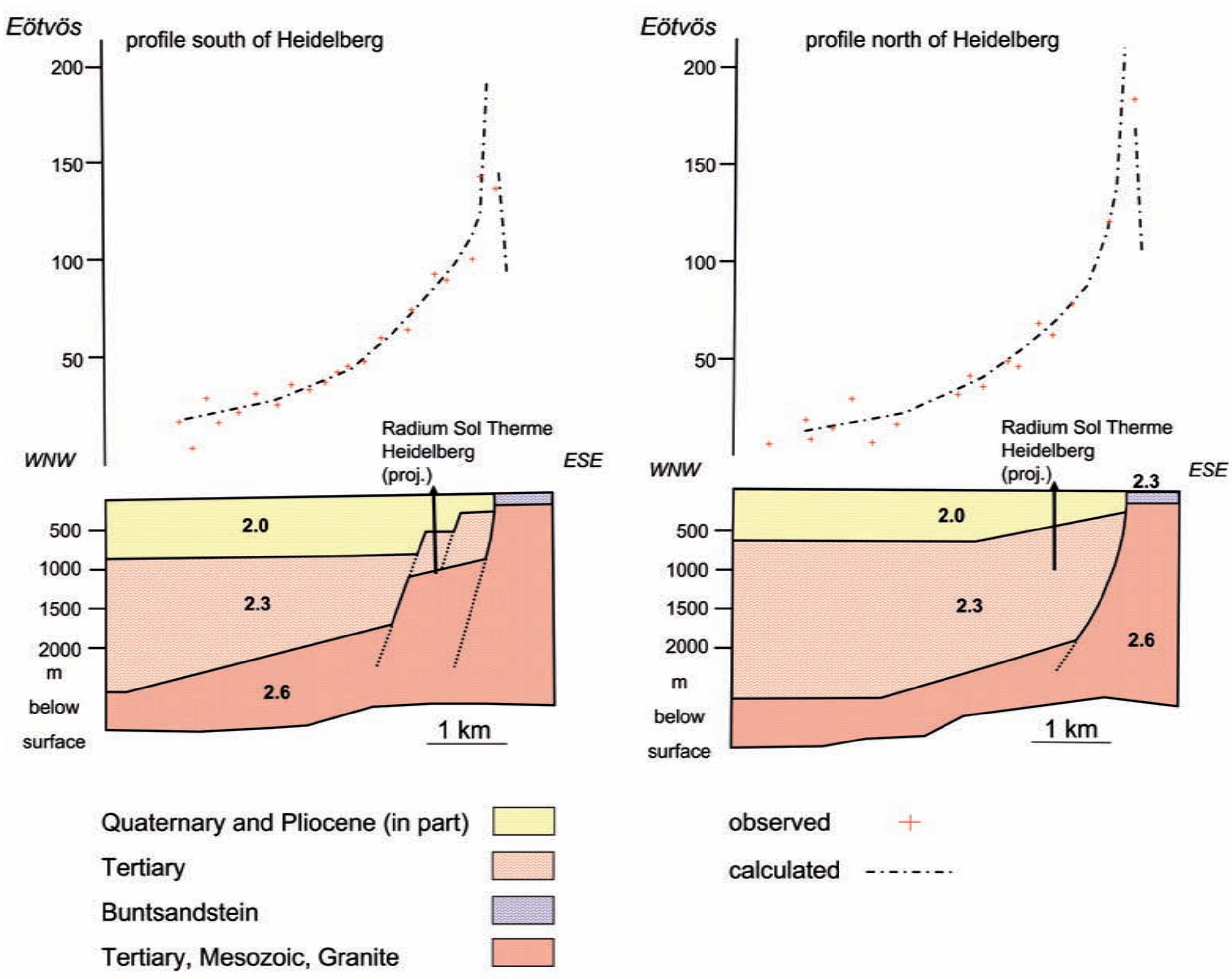

Fig. 6: First quantitative interpretation of the horizontal gradient (in Eotvös, 1 E = 10^{-9} s^{-2} = 0.1 mGal/km) of the gravity field related to the sediments of the Heidelberg Basin after CLOSS (1943). No density contrasts in the basement are considered, although a strong lateral variation of density must be assumed. The dip of the youngest sediments towards the west contradicts the new reflection seismic data.

Abb. 6: Erste quantitative Interpretation des Horizontalgradienten (in Eotvös, 1 E = 10^{-9} s^{-2} = 0.1 mGal/km) des Schwerefeldes im Hinblick auf die Sedimente des Heidelberger Beckens nach CLOSS (1943). Obwohl von starken lateralen Dichtekontrasten im Basement auszugehen ist, werden diese nicht berücksichtigt. Das Einfallen der jüngsten Sedimente nach Westen steht im Widerspruch zu den neuen reflexionsseismischen Ergebnissen.

ments in the Upper Rhine Graben are known to have densities between 2350-2450 kg/m^3, strongly depending on the amount of evaporates in the Early Oligocene strata, at least in the southern part of the graben (Rotstein et al. 2006).

Interpreting the observed gravity anomalies only in terms of varying sediment thickness, two main centres of deposition can be distinguished: one between Heidelberg and the Rhine River, and the second northeast of Landau (Fig. 4). Considering the information about Base 'Quaternary' (Fig. 2), the anomaly close to Landau is not related to anomalously thick Quaternary deposits. The source of this anomaly must be assumed to be at greater depth. This source can be located either in the older sediments, e.g. thick deposits of Early Miocene age in agreement with Schumacher (2002), or in the basement, e.g. an extension of units that outcrop in the northern Odenwald today, to the southwest. Only the large negative gravity anomaly east of the Rhine River can be discussed in terms of varying thickness of Quaternary sediments, even though this interpretation is ambiguous. This anomaly is related, at least to some extent, to the 'Heidelberger Loch'. The Ludwigshafen boreholes are located on the western margin of this basin structure; the Heidelberg UniNord borehole close to the absolute gravity minimum. With respect to the map of 'Quaternary' sediments (Bartz 1974, improved by Haimberger, Hoppe & Schäfer 2005), the Heidelberg Basin extends further southwards, towards Karlsruhe. This extension cannot be traced unequivocally in the gravity map, where north and west of Karlsruhe a relative gravity high occurs. The contour lines delimiting this relative gravity high from the more distinct gravity low to the north strike nearly W-E, which is not in accordance with the map of Base 'Quaternary'. But these observations correspond well with the quantitative interpretation of the gravity anomalies south of Karlsruhe discussed previously and presented by Rotstein et al. (2006). High density Early Palaeozoic and Proterozoic rocks in the basement are suggested as source for this anomaly compensating the gravity effect of sediments.

First quantitative interpretations of the gravity field of the Heidelberg Basin were published by Closs (1943). Based on torsion balance data, models were derived that explain the observed horizontal gradient (in Eotvös, 1 E = 10^{-9} s^{-2} = 0.1 mGal/km) running from the Odenwald in the east about 5 km into the Upper Rhine Graben in the west (Fig. 6). Therefore, only the local situation at the eastern graben boundary fault was investigated. The thickness of Pleistocene and youngest Plicocene sediments is estimated to be ~ 500 m at the Heidelberg Uni-Nord location. Furthermore in Closs's model the uppermost sediment unit dips with about 45° towards west – strongly contradicting the result of the new reflection seismic surveys. Density contrasts in the crystalline basement of the URG in this region were not taken into account, although from the adjacent Odenwald a large variety of alkaline (high density) and acidic (lower density) rocks are known.

4 Seismic survey and data processing

Seismic measurements in urban areas often encounter considerable difficulties. Restrictions exist for seismic sources (only low-energy seismic sources, services lines, endangerment of supply lines, services pipes, traffic restrictions, etc.) as well as for the recording side (sealing of the surface, enhanced noise level, etc.). The design of seismic profiles is therefore more often dictated by logistics than by geological reasoning.

At the start of the project a borehole location in Heidelberg was proposed at the abandoned freight depot south of the Neckar River (Fig. 7). A 1.5 km long profile (profile 1) was therefore measured, that showed strong inclinations of deep reflectors. To check the true inclination of the reflectors, the data were supplemented by a second profile later on (profile 4). The profiles could not be connected to existing industry profiles (the next one being about 1.5 km apart to the SW), but the interpretation could be done by comparison of reflection patterns. The borehole Radium Sol Therme could barely be

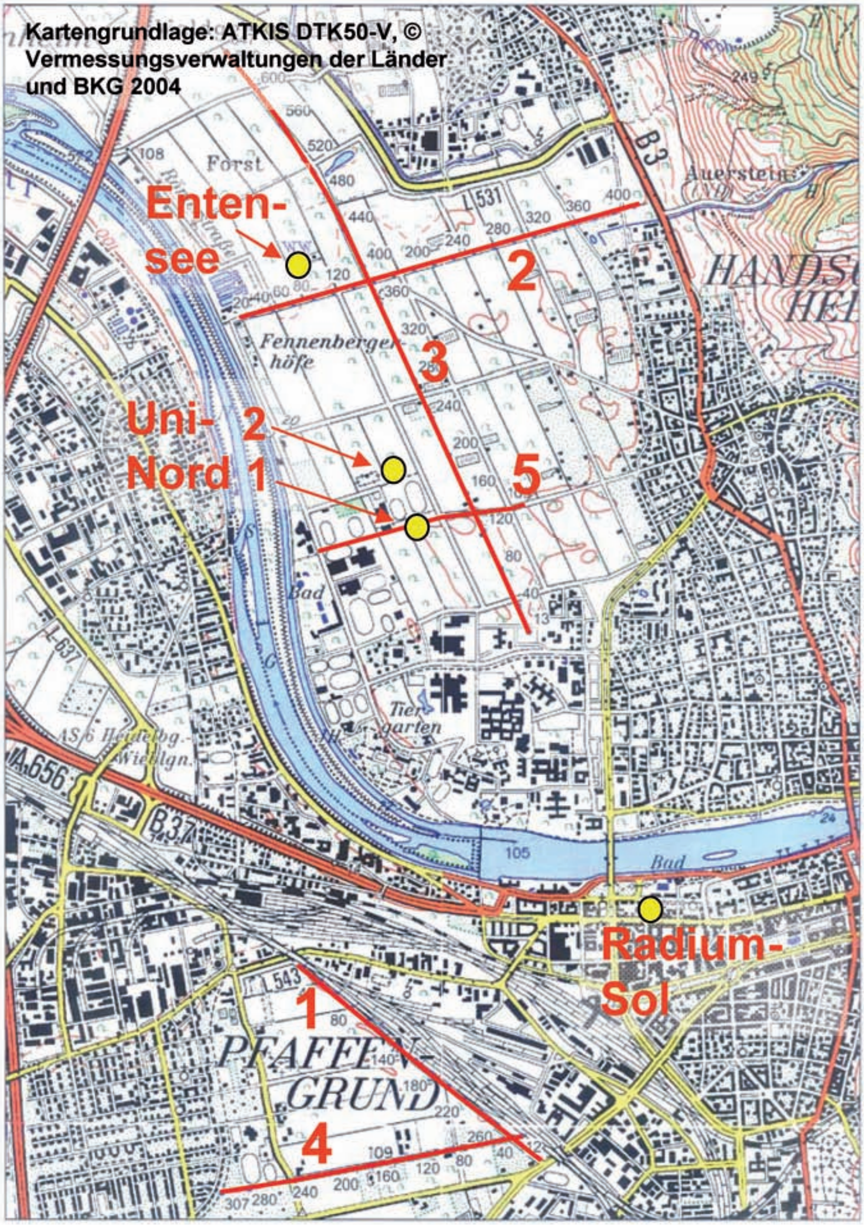

Fig. 7: Seismic reflection profiles (red lines) measured in Heidelberg. Yellow points indicate boreholes mentioned in this paper.

Abb. 7: In Heidelberg aufgezeichnete reflexionsseismische Profile (rote Linien). Gelbe Punkte markieren die in diesem Artikel genannten Bohrungen.

Fig. 8: Seismic hydraulic vibrator, constructed for near surface high resolution profiling.

Abb. 8: Seismischer Hydraulikvibrator, der für hoch auflösende oberflächennahe Messungen entwickelt wurde.

used for interpretation due to its controversial interpretation. In addition, data quality suffered due to extreme electromagnetic disturbances of 16 2/3 Hz and its multiples up to 500 Hz.
North of the Neckar River the building density is lower, improving the conditions for seismic measurements. First, a profile perpendicular to the general trend of faults was shot (profile 2). After some encouraging results, a longer north - south trending profile (profile 3) was registered. However, continuation to the exploration

Table 2: Recording parameters used in the reflection seismic surveys.

Tab. 2: Aufnahmeparameter der reflexionsseismischen Messungen.

	Profiles 1-4	profiles 5-7
Seismic source	GGA-vibrator MHV 2.7	GGA-vibrator MHV 2.7
Sweep	16 s linear, 30-180 Hz	16 s linear, 30-180 Hz
Recording length	20 s	20 s
Source/recording point distance	10 m / 10 m	5 m / 5 m
Reflexion point distance	5 m	2,5 m
Geophone type	SM4, 20 Hz	SM4, 20 Hz
Group length/geophones in group	5 / 6	- , 1
Spread	fixed spread (p. 1, 4) end on (p. 2,3)	end on
Recording instrument	Geometrics (StrataVisor or Geodes)	Geometrics (Geodes)
Recording mode	unstacked, uncorrelated	unstacked, uncorrelated
Number of channels	72 (p. 1,2), 120 (p. 3, 4)	120
Vertical stacks	4	2
Samplerate	1 ms	1 ms

borehole 'Schriesheim', about 1 km further north (Fig. 2), could not be established. After fixing the location of the research borehole 'Heidelberg UniNord 1', another short profile (profile 5) was shot to check for possible fault zones. In this area signal quality was degraded by waves originated from service pipes (called 'pipe waves' for simplicity further on). These are especially visible on profile 2 and profile 5. The two profiles at the Viernheim location (profiles 6 and 7 in Fig. 2) were laid out perpendicular to each other, with the proposed position of the research drilling at their crossing point. The profiles were surveyed in a forested area without further problems.

All profiles were shot by a small hydraulic vibrator (Fig. 8), which yields a maximum peak force of 30 kN and a frequency range of 20 - 500 Hz (for recording parameters cp. Table 2). This vibrator was developed especially for high-resolution shallow profiling (Buness & Wiederhold 1999, van der Veen et al. 2000). It is very appropriate for use in an urban environment, due to its relatively low impact on the surface, compared to e.g. weight dropping or other impulsive sources. Data were processed using a commercial processing system (ProMAX, Landmark Corp.). Processing steps are listed in Table 3, details regarding the single steps are discussed e.g. in Yilmaz (2001). In addition, to the processing steps listed in Table 3, waves in profiles 2 and 5 were suppressed by trace-mixing algorithms. Trace mixing, although a very simple algorithm, proved to be most effective of a variety of other algorithms, including spatial 2D filters, f-k based filters and eigenvector filtering. However, the incoherency of this kind of noise prevents elimination without damaging the reflection signal.

The velocity fields for finite-difference migration and for the subsequent depth conversion were derived from the smoothed stacking velocity fields. The deviations from the velocities derived by the VSP (vertical seismic profile) measurements carried out in the UniNord 1 borehole down to a depth of 180 m turned out to be very small, hence the former were kept during later processing. The structure of the uppermost low velocity layer down to a depth of 20 m could not be determined adequately, causing some uncertainty about the overall depth level of the profiles. As a consequence the depth level was calibrated using the VSP reflections, which have a known depth. A reference level of 100 m a.s.l. was chosen for all profiles.

Table 3: Typical data processing flow

Tab. 3: Typischer Prozessingsablauf

1.	correlation with field sweep
2.	quality control
3.	vertical stack
4.	automatic gain control 300 ms
5.	deconvolution (spiking, zero phase, 30 ms operator)
6.	bandpass 30-180 Hz, 24db/oct.
7.	surgical mute of surface waves and shear waves
8.	attenuation of air-coupled waves
9.	refraction static to floating datum
10.	velocity analysis and iterative application of residual static (initial step with lowpass 90 Hz)
11.	stack to final datum (100m)
12.	FX deconvolution (60 – 180 Hz)
13.	automatic gain control 500 ms
14.	FD migration
15.	depth conversion

5 Results

Heidelberg – the region north of the Neckar River

The profile which is best tied to an existing deep borehole is the north-south trending profile 3 in the area north of the Neckar River: the Schriesheim borehole is located about 1 km further north (Fig. 2). Although no direct connection between the newer seismic line and the borehole exists, the geological structures can be controlled by hydrocarbon seismic lines. Both, E-W and N-S trending profiles that cross the Schriesheim borehole are available.

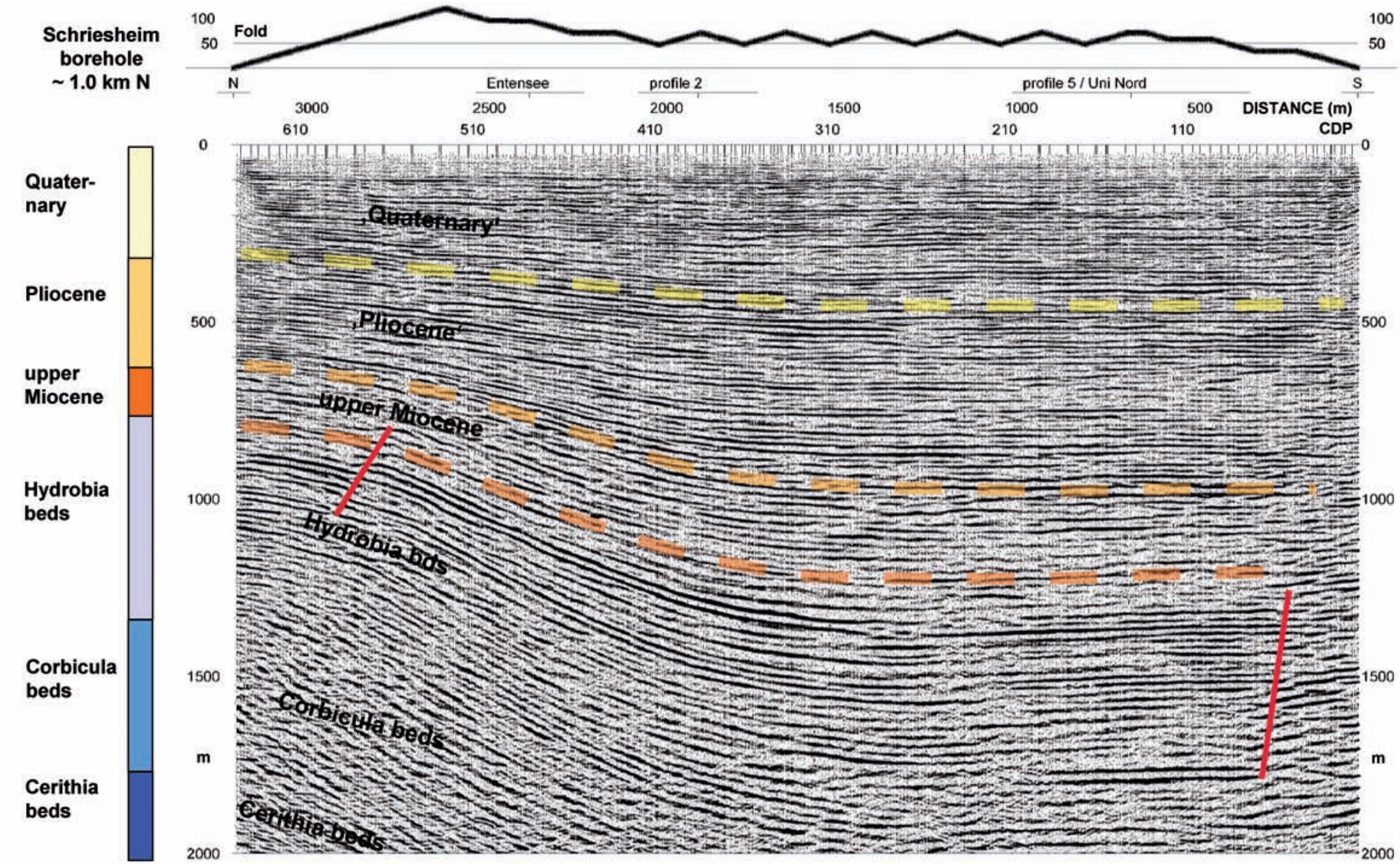

Fig. 9: Migrated seismic reflection profile 3. The 2650 m deep borehole 'Schriesheim' is located about 1 km north of profile 3.

Abb. 9: Migriertes reflexionsseismisches Profil 3. Die 2650 m tiefe Bohrung 'Schriesheim' liegt etwa 1 km nördlich des Profils 3.

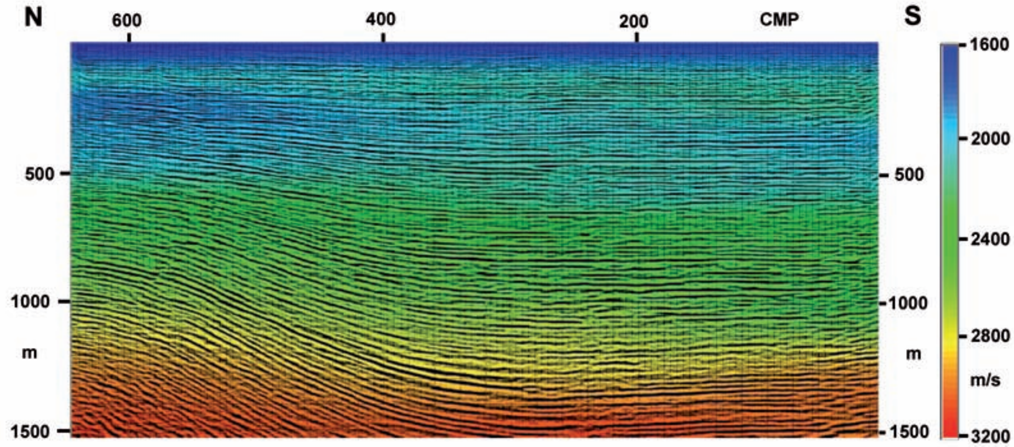

Fig. 10: Estimation of the interval velocity field along reflection profile 3 derived from stacking velocities. The colour-coded interval velocities are overlain by the migrated seismic section shown in Fig. 9.

Abb. 10: Intervallgeschwindigkeiten abgeschätzt aus Stapelgeschwindigkeiten entlang des Profils 3. Die farbkodierten Intervallgeschwindigkeiten sind von dem in Abb. 9 dargestellten migrierten seismischen Profil überlagert.

Fig. 9 shows the preliminary stratigraphical interpretation of profile 3 that considers Base 'Quaternary' and Base Late Miocene. Only based on seismic data, the separation between these units remains ambiguous because of missing continuous reflections, e.g. Base 'Quaternary'. Furthermore, no distinct changes in the reflection patterns mark these boundaries.

Concerning deposits of Quaternary age, segments with strong continuous reflections that reveal correlation lengths in the order of 500 to 1000 m alternate laterally with sections characterised by low reflection energy and sub-parallel deposition. This can be interpreted in the sense of repeating changes of the depositional environment. At the southern end of the profile, where subsidence was greatest, more continuous reflections become apparent in the deeper part of the Pleistocene than in the north. A throughout, low-reflective, sub-parallel bumpy to chaotic reflection pattern as described by HAIMBERGER, HOPPE & SCHÄFER (2005) for some parts of the river seismic along the Rhine was not observed in our sections. This gives some evidence for lateral changes of the depositional environments.

The reflection patterns caused by the underlying Pliocene and Miocene strata consist of more continuous reflections. Especially in the most southern part of profile 3, some areas at depths between 600 and 700 m are of low reflectivity. The most distinct reflector appears just below the top of the *Hydrobia* beds.

The additional subsidence in the 'Heidelberger Loch' – the depocentre of the Heidelberg Basin – amounts to 160 m, with respect to the transition Pliocene / Pleistocene and 300 m with respect to Base Pliocene. This subsidence is not linked to any faults with large displacements but to flexures of the beds that were probably formed syn-sedimentarily. Faults with distinct displacements are related to the upper strata of the *Hydrobia* beds only. At the northern end of profile 3, normal faulting is observed. The fault interpreted at the southern end of the profile reveals a pattern that is typical for diffractions although the section is migrated and therefore no diffraction should occur. But this holds only if the fault strikes perpendicular to the seismic profile. Consequently a large fault, proximately south of the profile, is assumed parallel to the course of the Neckar River.

Often, the seismic velocity field images geological structures by sharp vertical and lateral velocity changes. But for the area of the

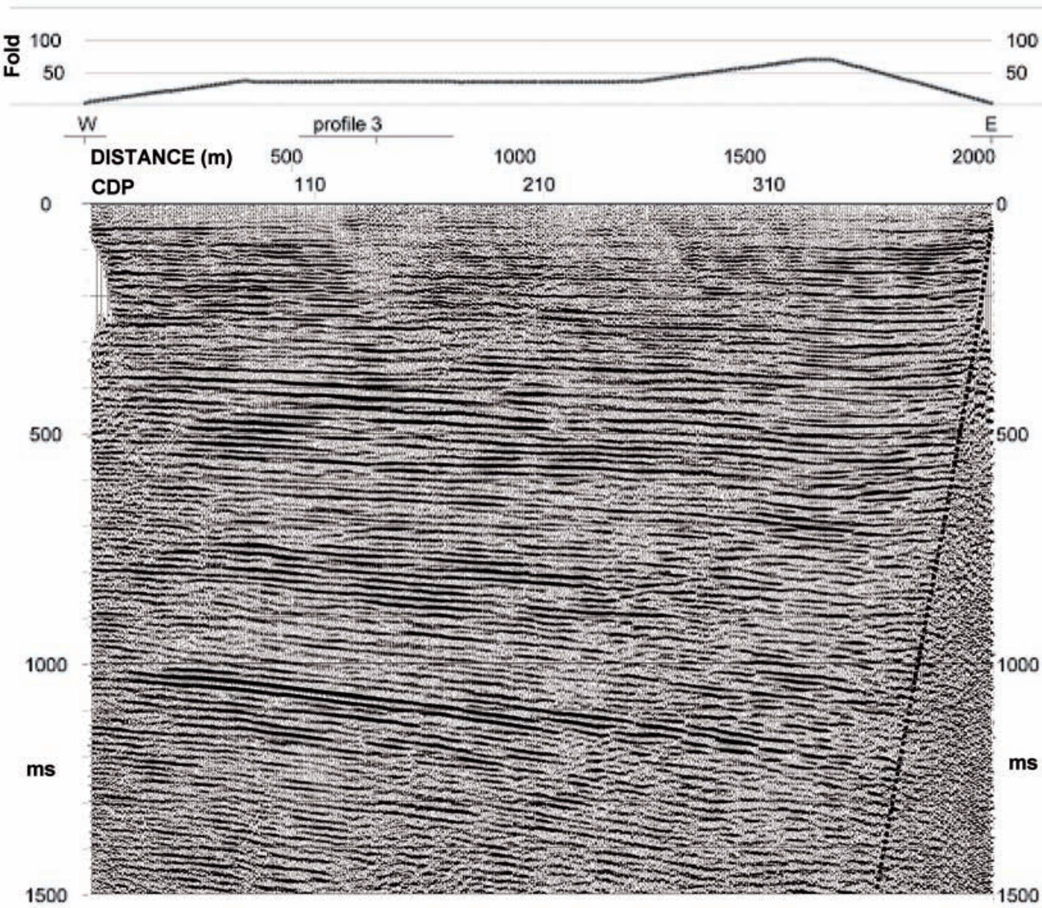

Fig. 11: Stacked seismic reflection profile 2 in time domain, unmigrated. Areas with very low reflectivity in the upper 300 ms in the central part of the profile are due to strong noise and do not reflect geology. A wedge-shaped zone at the eastern edge of the profile, indicated by a dotted line, maybe caused by the transition of the sedimentary infill of the URG to the crystalline basement of the Odenwald.

Abb. 11: Gestapeltes reflexionsseismisches Profil 2 im Zeitbereich, unmigriert. Die stellenweise sehr geringe Reflektivität in den oberen 300 ms in zentralen Teil des Profils wird nicht durch die Geologie, sondern durch starke Störungen hervorgerufen. Eine keilförmige, durch eine punktierte Linie markierte Zone am Ostrand des Profils kann durch den Übergang von der Sedimentfüllung der ORG zum kristallinen Grundgebirge des Odenwaldes verursacht werden.

Heidelberg Basin investigated with the new reflection lines no distinct information is provided by the velocity fields. An estimation of the velocity field of profile 3 (Fig. 10) reveals interval velocities that increase gradually from 1600 m/s near the surface to 3200 m/s at a depth of 1500 m. These velocities are deduced from stacking velocities, which do not constitute physical seismic velocities, since they are affected by layer dips, side reflections, diffractions and other seismic particularities. The reliability of stacking velocities decreases strongly with depth, depending on the maximum offset of the seismic survey. The velocities cannot be controlled by other methods, e.g. VSP measurement, due to the lack of deep VSP (vertical seismic profile) or sonic measurements. However, they coincide

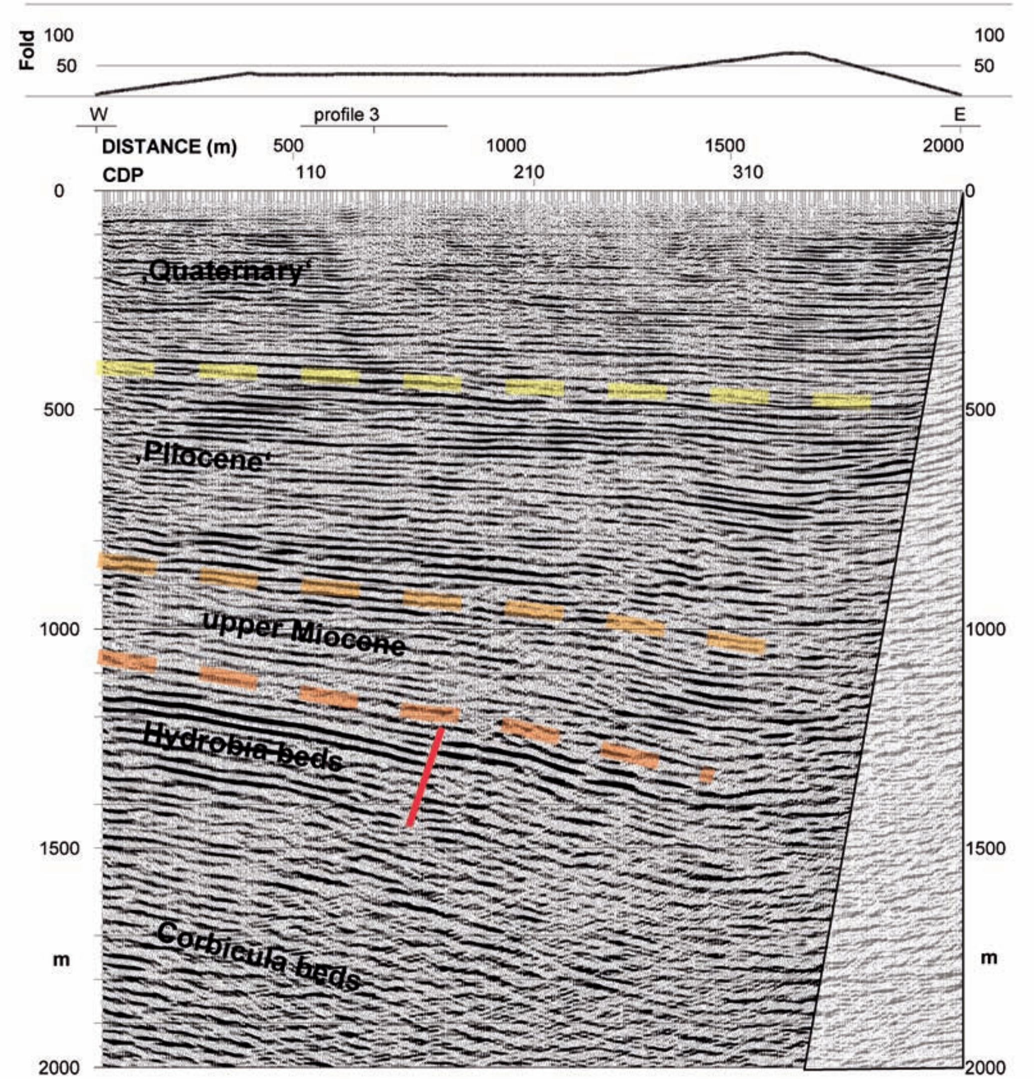

Fig. 12: Migrated seismic reflection profile 2. Seismic signals inside the transparent triangle are not interpretable because of geometrical reasons and migration artefacts. The strongly-bent reflectors close to the triangle zone maybe caused by drag folding.

Abb 12: Migriertes reflexionsseismisches Profil 2. Seismische Signale innerhalb des transparenten Dreiecks können aufgrund der geometrischen Verhältnisse sowie von Migrationsartefakten nicht interpretiert werden. Die stark gekrümmten Reflektoren unmittelbar neben diesem Dreieck könnten auf eine Schleppfalte deuten.

quite well with the regional velocity trend derived from deep boreholes in the Heidelberg Basin. A remarkable feature is a zone of low velocity, which has a depth of approximately 180 – 250 m at the northern edge of the profile and of 300 - 450 m at its southern edge. The upper limit of this zone corresponds therefore well with the lower boundary of the coarse-grained Weinheim beds (cf. Fig. 3).

Profile 2 is located between the Neckar River and the eastern boundary fault of the Upper Rhine Graben (see Fig. 7). The profile approaches at its eastern edge the topographic border of the URG and hence the master boundary fault of the URG.

Both the unmigrated time section (Fig. 11) and the migrated depth section (Fig. 12) are presented, so the reader can better judge the influence of the migration processing step. Generally, the reflections dip to the east, with dips becoming greater with increasing depth. A wedge-shaped zone at the easternmost position (marked by the dotted line in Fig. 11) shows no coherent signal. This wedge is probably due to the eastern master fault which juxtaposes the sedimentary infill of the URG against the crystalline basement of the Odenwald. A very rough estimation of its dip yields values of approximately 80°. Adjacent to this wedge, flat or slightly westward dipping reflectors are displayed at travel times greater 700 ms. This feature is interpreted as a drag fold. Below 700 ms, reflections again dip towards east. Some hints for diffractions can be seen, that could be caused by the fault zone (e.g. CMP 260 at 800 ms). Areas of apparently low reflectivity as observed in the youngest Quaternary, e.g. between CMP 110 and CMP 310, are caused by strong noise due to pipe waves.

After migration (Fig. 12), the bending of the sediment strata next to the assumed boundary fault becomes more obvious. However, it is difficult to separate real reflections from migration artefacts that always occur at the ends of a seismic profile. Signals inside the marked triangle should not be considered as real reflectors. The continuous subsidence of sediments beneath the central and western part of the profile is revealed by an increasing dip angle with depth. The apparent dip of Base 'Quaternary' is 1.5° towards east and 4.5° for Base Pliocene. A fault with a distinct displacement is again only visible in the upper part of the *Hydrobia* beds.

Profile 5 was recorded with modified acquisition parameters (smaller CMP spacing, smaller offset, cp. Table 2), which yielded a higher resolution (Fig. 13). Again, in the eastern part the image of Quaternary deposits is significantly affected by pipe waves. At depths between 600 and 700 m, reduced reflectivity is observed at the western end of the profile. The dip angles of Base 'Quaternary' and Base Pliocene, 2° and 6° respectively, are slightly increased with respect to those of profile 2.

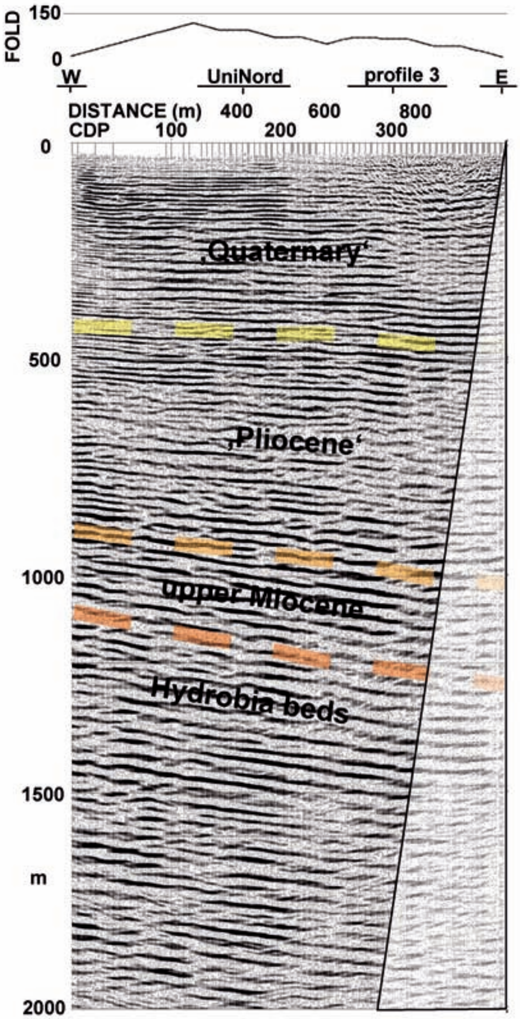

Fig. 13: Migrated seismic reflection profile 5. No seismic information is available inside the transparent triangle for geometric reasons.

Abb. 13: Migriertes reflexionsseismisches Profil 5. Aufgrund der geometrischen Verhältnisse sind innerhalb des transparenten Dreiecks keine seismischen Informationen verfügbar.

In the 'Heidelberg UniNord 1' borehole in 2006 (Ellwanger et al. 2008), a vertical seismic profile (VSP) was recorded (Fig. 14), as well as numerous other geophysical logging methods (Hunze & Wonik 2008). To ensure comparability with the reflection seismic profiles, the same vibrator and the same field parameters

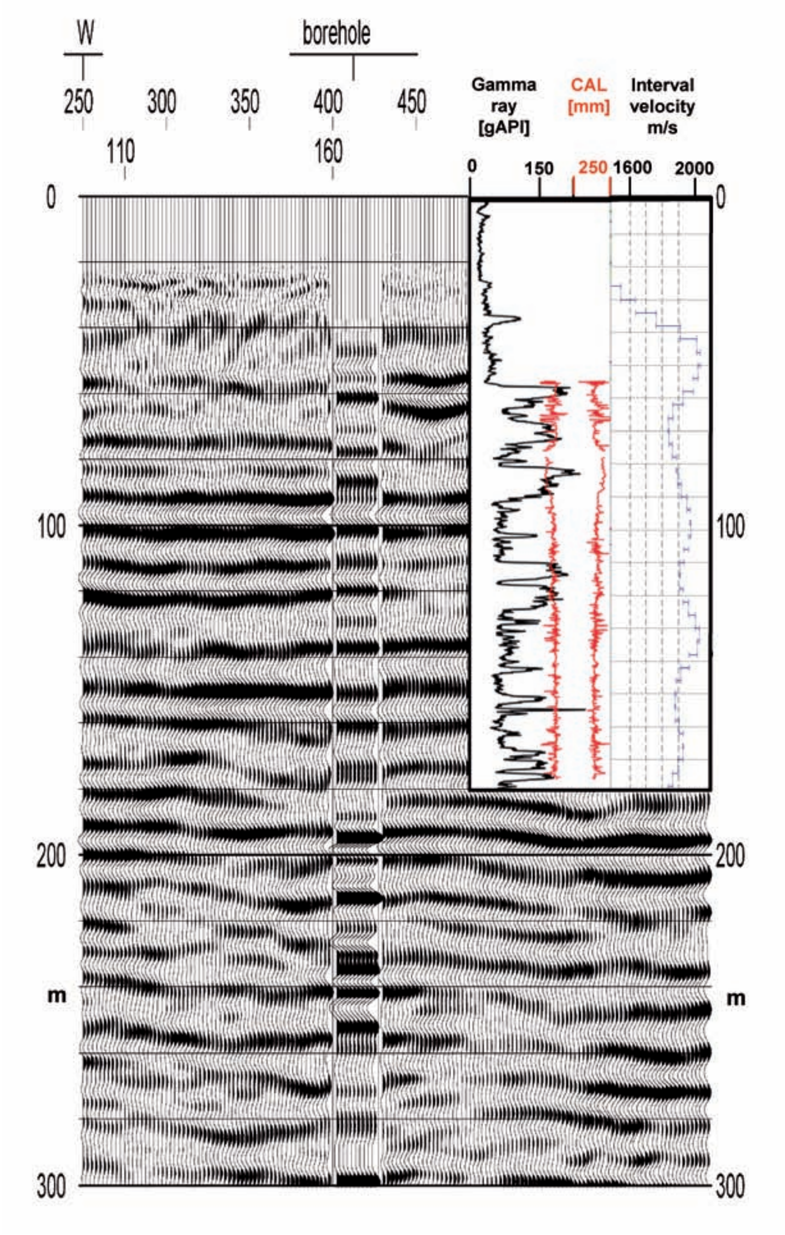

Fig. 14: Detail of seismic profile 5 (cf. Fig. 13) with corridor stack of the VSP (borehole location UniNord 1) inserted. Upper right: gamma ray log, calliper log (after HUNZE & WONIK 2008), and interval velocities deduced from the VSP. Reference level is surface level at the borehole location (107 m). Depth conversion is based on VSP-derived velocities down to 180 m depth.

Abb. 14: Ausschnitt aus dem seismischen Profil 5 (vgl. Abb. 13) mit dem Korridor Stack des VSPs (Bohrlokation UniNord 1). Oben rechts: Gamma Log (nach HUNZE & WONIK 2008), Bohrlochdurchmesser sowie die aus dem VSP abgeleiteten Intervallgeschwindigkeiten. Bezugsniveau ist die Ansatzhöhe des Bohrpunktes (107 m). Die Tiefenkonvertierung basiert auf den aus dem VSP bis 180 m Tiefe abgeleiteten Geschwindigkeiten.

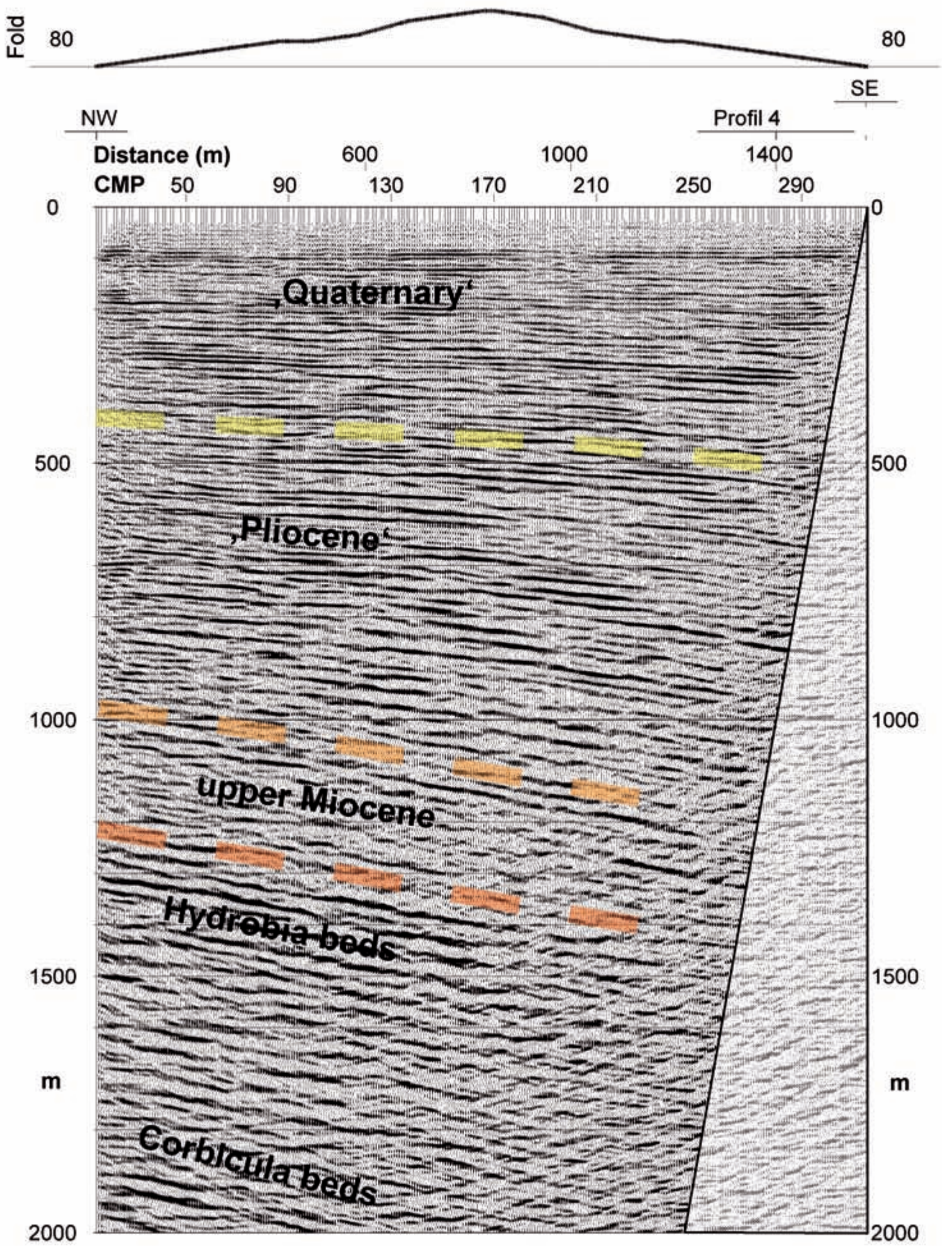

Fig. 15: Migrated seismic reflection profile 1. No seismic information is available inside the transparent triangle for geometric reasons. The strongly northwest-dipping reflectors close to the triangle zone are probably artefacts caused by migration.

Abb. 15: Migriertes reflexionsseismisches Profil 1. Aufgrund der geometrischen Verhältnisse sind innerhalb des transparenten Dreiecks keine seismischen Informationen verfügbar. Die stark nach Nordwesten einfallenden Reflektoren unmittelbar neben diesem Dreieck stellen wahrscheinlich durch die Migration verursachte Artefakte dar.

were used (Table 2). A depth interval from 180 m to 32 m could be measured with a recording distance of 4 m. Several surveys were dependant on the accessible openhole interval. Signal quality is very good and allows an unequivocal determination of traveltimes and the locally-reflected wavefield.
Interval velocities vary between 1850 m/s and 2250 m/s, beside a zone of lower velocity near the surface. A correlation can be observed between the seismic velocity and other petrophysical parameters: low values of the gamma ray log (coarse-clastic material) correlate with high velocities and high values of the gamma ray log (fine-clastic material) with low velocities. The VSP-derived velocities resemble very closely the smoothed stacking velocities derived from profile 5.
The VSP corridor stack represents the locally-reflected wavefield and corresponds with the surface reflection profiling results. Small discrepancies, as seen in Fig. 14, can be explained by different field geometries and recorded frequencies. The corridor stack was used to calibrate the total static of the reflection seismic lines, since the depths of its reflections are determined directly.

Heidelberg – the region south of the Neckar River

The new reflection seismic profiles 1 and 4 (Figs. 15, 16) are located south of the Neckar River (see Fig. 7). Therefore a tie to existing deep wells is hardly possible. The observed reflection patterns cannot be easily correlated with those of the hydrocarbon seismic lines, as assumed prior to the surveys. Therefore, the information from the Schriesheim well was correlated along several seismic lines and transferred to the nearest seismic profile recorded by the hydrocarbon industry, which is about 1,5 km south of profile 4. But the interpretation of the youngest sediments, e.g. Quaternary, remains especially uncertain, because these were not imaged well in the industrial seismic lines.
Both profiles 1 and 4 intersect each other at an angle of about 50°. Again, on both profiles the apparent dip of the sediment fill increases with depth. For Base 'Quaternary' it amounts to 3°, for Base Pliocene it amounts to 9° (profile 1) and 11° (profile 4). Therefore, real dip is about 4° for the Base 'Quaternary' and 11° for the Base Pliocene, in each case towards east. This is about twice as much as these beds north of the Neckar River have.
Similar to profile 3, Quaternary deposits show quasi-continuous reflections (e.g. profile 1 in 300 m depth), alternating with weak and partly sub-parallel reflections. Within the *Hydrobia* beds again a strong reflector occurs that is also visible on the other seismic sections.

Viernheim

In contrast to the seismic profiles recorded in the Heidelberg area the seismic lines recorded in the vicinity of the Viernheim borehole (Figs. 17, 18) allow a distinct classification of the sediment fill. Tops of zones of high reflectivity are visible at both depths of 220 m and 570 m, whereas especially the depth interval between 450 m and 570 m shows low reflectivity.
Considering the results of the research borehole Viernheim (Hoselmann 2008) the reflector at a depth of 228 m can be assigned to the transition between the 'Quaternary' and the underlying material of local provenance (reference height of the seismic line is 100 m above sea level, the drilling site is 97 m above sea level). The limnic-fluviatile deposits of local provenance cause the observed high reflectivity.
Due to the high quality of the Viernheim data a complex fault pattern can be identified. Especially on the E-W oriented profile 6 (Fig. 17), a fault zone is observed that runs through all prominent reflection horizons and penetrates deep into the Rhenish facies, e.g. into 'Pleistocene' sediments. Originally a drilling location close to the intersection of profiles 6 and 7 was favoured. Based on these seismic results it was shifted by about 500 m towards south where the sediment succession was expected to be less affected by faults.
Due to the acquisition parameters and the processing of the seismic data, reflectors above

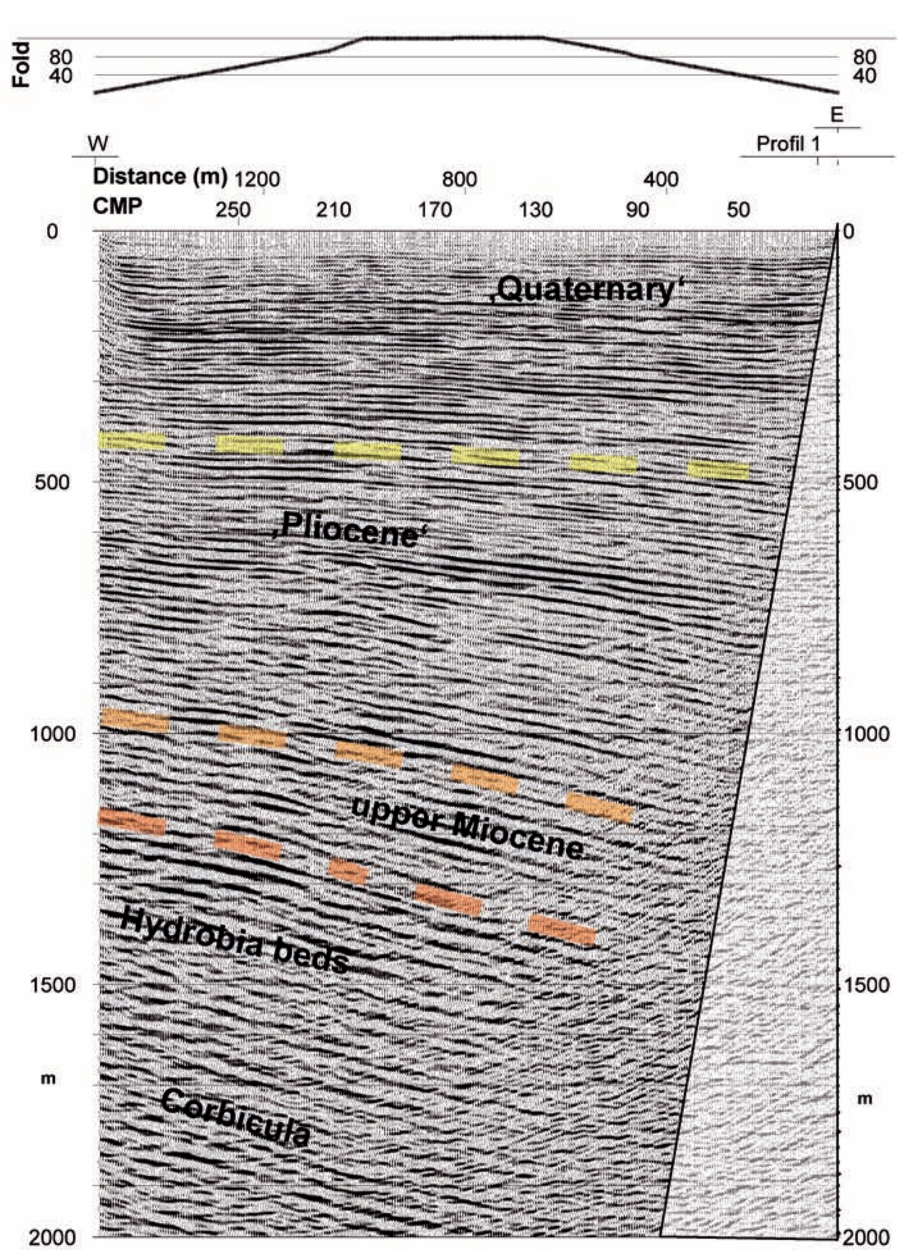

Fig. 16: Migrated seismic reflection profile 4. No seismic information is available inside the transparent triangle for geometric reasons. The strongly west-dipping reflectors close to the triangle zone are probably artefacts caused by migration.

Abb. 16: Migriertes reflexionsseismisches Profil 4. Aufgrund der geometrischen Verhältnisse sind innerhalb des transparenten Dreiecks sind keine seismischen Informationen verfügbar. Die stark nach Westen einfallenden Reflektoren unmittelbar neben diesem Dreieck stellen wahrscheinlich durch die Migration verursachte Artefakte dar.

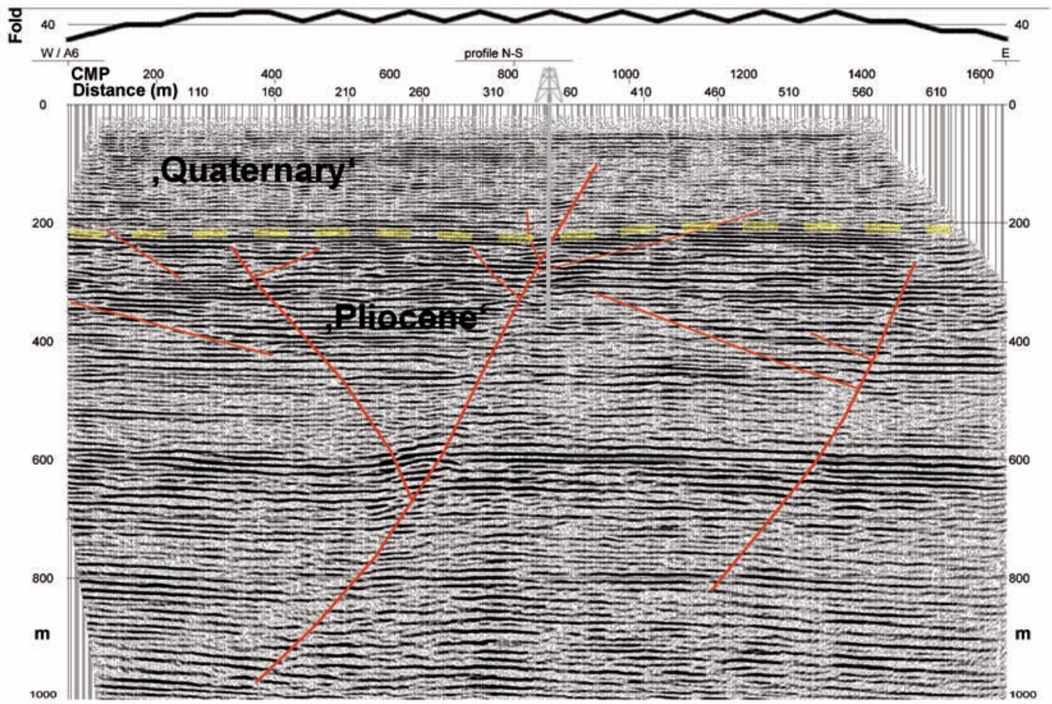

Fig. 17: Migrated seismic reflection profile 6 near Viernheim. The initially-proposed borehole location (marked by a derrick) was abandoned after the seismic became available to avoid the predicted faults. The location was than shifted about 500 m to the south (see Fig. 18).

Abb. 17: Migriertes reflexionsseismisches Profil 6 bei Viernheim. Der ursprünglich vorgeschlagene Bohrpunkt (Bohrturm) wurde aufgegeben, nachdem die Seismik verfügbar war, um ein Durchbohren der prognostizierten Störungen zu vermeiden. Der Bohrpunkt wurde sodann ungefähr 500 m nach Süden verschoben (vgl. Abb. 18).

35 m depth cannot be mapped. The first strong reflection that can be correlated along the entire profile is imaged at 40 m depth, two more are found at 80 m and 180 m depth. The uppermost two reflectors are most probably related to the top and the base of the Ladenburg Horizon, a prominent fine-grained horizon in the Upper Rhine Graben (in hydrostratigraphy named the 'Oberer Zwischenhorizont').

A precise and detailed stratigraphic interpretation of the reflectors below 570 m depth was not possible, because these were not reached by the research borehole. Instead we intend to achieve this by using industrial reflection seismic data, which is much denser than in the Heidelberg area.

6 Discussion and Conclusion

For the Heidelberg Basin thick sediment sequences are apparent, both in gravity and seismic data. Quantitative interpretation remain preliminary, as long as no deep boreholes can be included and 3-D models based on gravimetric and seismic data can be calculated, that additionally consider data from the hydrocarbon industry.

The seismic data at the locations of Viernheim and Heidelberg show quite different images, indicating varying sedimentological processes throughout the Heidelberg Basin. Confirming this, seismic measurements along the Rhine River (HAIMBERGER, HOPPE & SCHÄFER 2005, BERTRAND et al. 2006) show yet other seismic

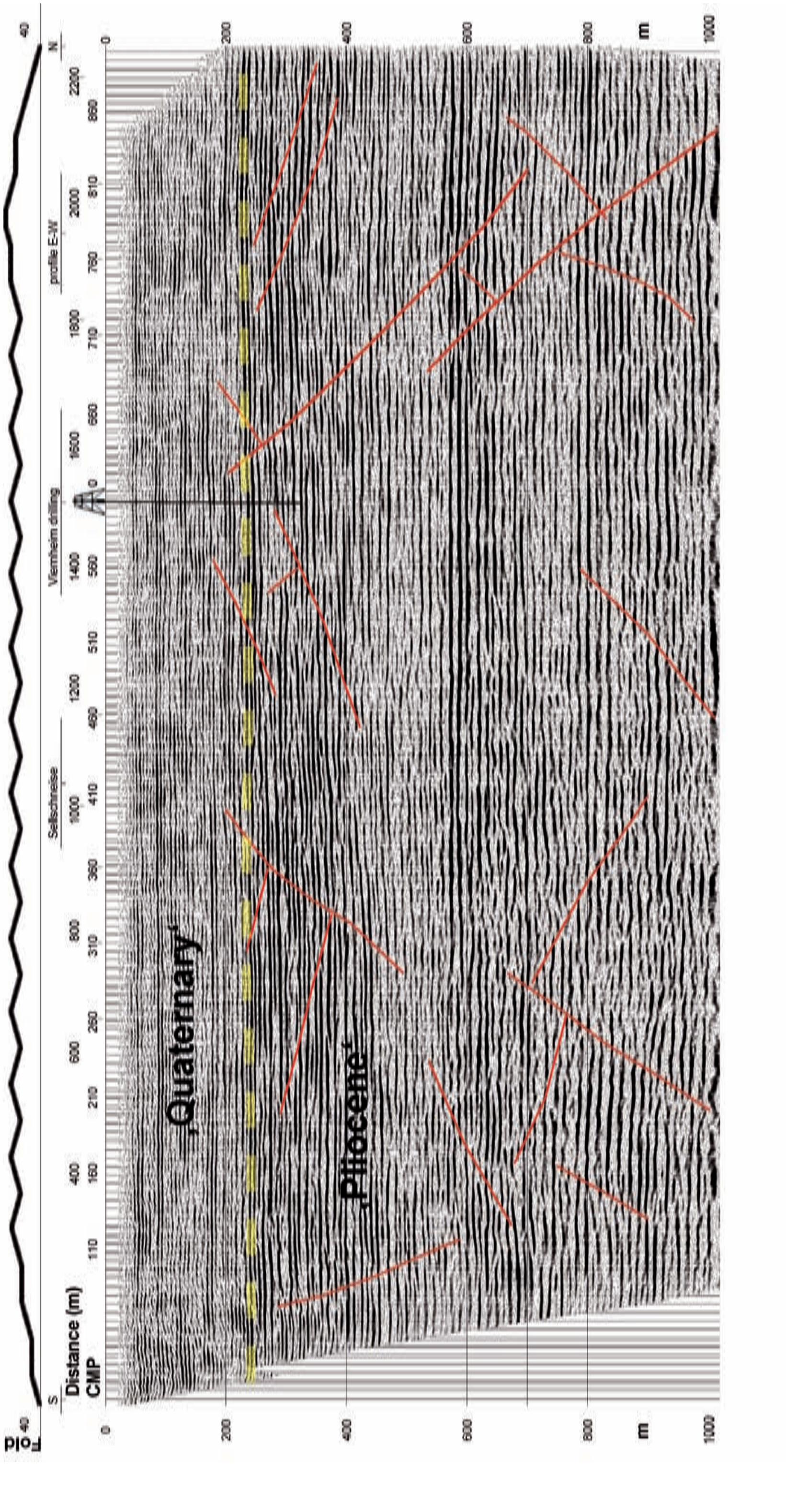

Fig. 18: Migrated seismic reflection profile 7. The Viernheim borehole location is indicated.

Abb. 18: Migriertes reflexionsseismisches Profil 7. Die Bohrlokation Viernheim ist eingezeichnet.

characteristics. Therefore a consistent seismic stratigraphy for the Plio-/Pleistocene sediments of the URG is not achievable within the limits of the presently applied inconsistent stratigraphic scenarios.

Concerning the location of the Viernheim boreholes, two new reflection seismic profiles image a sedimentary environment that is affected by tectonics, as documented by several faults. But these faults are mainly restricted to older sediments, e.g. to depths greater than about 225 m (Pliocene and older according to Hoselmann 2008). In contrast, during the Quaternary the tectonic activity seems to be quiet. Along the entire profile these sediments are horizontal. But on a smaller scale much more detailed information is imaged by the two seismic lines indicating a complex depositional system, especially during Pliocene or even older times. Considering the results of the Viernheim research borehole, the top and the base of a fine-grained horizon, comprising the Ladenburg Horizon (Oberer Zwischenhorizont) at about 40 and 80 m, respectively, depths can be traced in the seismic section. Reflections at a depth of about 180 m can be correlated with a sequence of regional distributed fine-grained sediments (Unterer Zwischenhorizont).

The top of the uppermost section of high reflectivity can be correlated with the transition from the Rhenish facies (alpine) sediments to material with local provenance at a depth of 225 m, as revealed by heavy mineral analysis, carbonate content, and petrography (Hoselmann 2008). Whether this seismic reflector can be interpreted as the transition Plio-/Pleistocene must be investigated by additional palynological studies that are not yet available.

The most important result derived from the seismic pre-site survey at the Heidelberg UniNord location is the existence of a subbasin in the Heidelberg Basin close to the eastern margin of the Upper Rhine Graben. The additional subsidence adds up to some hundred meters with respect to deeper strata, as imaged on profile 3, e.g. about 400 m for the top of the *Hydrobia* beds. All recorded profiles do not show any disconformities, faults are restricted to early Miocene (*Hydrobia* beds or older) units. However, this observation does not exclude potential hiatuses, which cannot be imaged by reflection seismic data.

By tying the new reflection lines to the Schriesheim well, the transition Pliocene to Pleistocene was predicted at depths between 400 and 500 m. This statement was based on the assumption that the extrapolation of information of the industry seismic lines across the gap between the northern end of the seismic profile 3 and the location of the Schriesheim borehole is correct. Furthermore using the interpretation of Base 'Quaternary' from a hydrocarbon well is uncertain because information is not available on the kind of data it is based on. Work done in the framework of hydrocarbon exploration was focused on deep structures rather than on young sediments.

The seismic lines reveal more or less continuous subsidence. The dip of sediments towards east increases with depth, showing a classical rollover anticline structure at the eastern URG master fault. The amount of subsidence increases from north to south: the Base Pliocene dips east by about 4.5 % on profile 2, 6 % on profile 5 and 11 % on profile 1 and 4. These values make a major fault zone beneath the Neckar River plausible, of which indications can be found at the southern end of profile 3. Differential compaction may have played a role by increasing the dip of the Miocene and younger strata. The rollover structure is not found to the north, as well as to the south of the 'Heidelberger Loch', as inferred from industry seismic profiles, which affirms it as the area with the most rapid subsidence.

Due to the thick sequences of Plio-/Pleistocene sediments, the research boreholes Heidelberg UniNord reveals a unique high temporal resolution. From the first Heidelberg borehole in 2006 a time marker of the Waalian stage is reported at 183 m – 210 m depth (Hahne, Ellwanger & Stritzke 2008). As the age of the Waalian is considered to amount to 1.5 Ma, and assuming continuous sedimentation, the Top of the Pliocene at 2.6 Ma has to be expected at only 365 m depth. However, the preliminary interpretation of the new reflection seismic profiles reveals Base 'Quaternary' first at about 430 m depth. Consequently, concerning the early Quaternary, increased sedimentation rates can be expected.

To aim on a deeper understanding of the basin genesis, a crucial point in the chronostratigraphic interpretation of seismic reflectors will be the proper definition of 'Base Quaternary'. A major step is also expected once the new drillings will be interpreted and correlated using the tools of sequence stratigraphy (Ellwanger et al. 2008). We are convinced that this will also include a consistent seismic scenario.

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Sediment Input into the Heidelberg Basin as determined from Downhole Logs

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Abstract: The Upper Rhine Graben, and the Heidelberg Basin in particular, play an important role in the investigation of climate change and tectonic activity during the Tertiary and Quaternary periods. Several research boreholes were recently drilled to acquire data for a new interpretation of the geology of the northern Upper Rhine Graben. This paper investigates in detail the boreholes at Heidelberg, Viernheim and Ludwigshafen-Parkinsel, as well as the shallower boreholes at Pfungstadt, Stadtwerke Viernheim and Hüttenfeld, in terms of their geophysical parameters. The physical properties of the lithologies described in the cores are characterised on the basis of borehole logging data. A hole-to-hole correlation between adjacent boreholes is then conducted, using the characteristic changes in the 'natural radioactivity' parameter to acquire information on changes in sediment provenance (Rhine, Neckar, Pfälzerwald and Odenwald). An interpretation applying the statistical method of cluster analysis allows identification of sections with homogenous physical properties from downhole measurements and thus the determination of possible sediment provenance.

[Interpretation des Sedimentationsgeschehens im Heidelberger Becken anhand von Bohrlochmessungen]

Kurzfassung: Der Oberrheingraben und insbesondere das Heidelberger Becken spielen eine Schlüsselrolle bei der Untersuchung der Änderungen im Klima und der tektonischen Aktivitäten im Tertiär und Quartär. In den letzten Jahren wurden einige Forschungsbohrungen abgeteuft, um Daten für eine neue Interpretation der Geologie des nördlichen Oberrheingrabens zu erhalten. Im Rahmen dieser Arbeit werden die Bohrungen Heidelberg, Viernheim und Ludwigshafen-Parkinsel sowie die flacheren Bohrungen Pfungstadt, Stadtwerke Viernheim and Hüttenfeld anhand der dort durchgeführten geophysikalischen Bohrlochmessungen näher untersucht. Die physikalischen Eigenschaften der einzelnen an den Kernen beschriebenen Lithologien werden mit Hilfe der Daten der Bohrlochmessungen charakterisiert. Anschließend erfolgt eine Korrelation zwischen benachbarten Bohrlöchern, um aus den charakteristischen Änderungen im Parameter ‚natürliche Radioaktivität' Aussagen zur Änderung der sedimentären Liefergebiete (Rhein, Neckar, Pfälzerwald und Odenwald) zu treffen. Eine Auswertung mit der statistischen Methode der Clusteranalyse ermöglicht es, aus den Bohrlochmessungen Bereiche mit einheitlichen physikalischen Eigenschaften zu finden und damit die möglichen sedimentären Liefergebiete einzugrenzen.

Keywords: Heidelberg Basin, downhole logging, hole-to-hole correlation, sediment provenance

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1 Introduction

1.1 Geology

One of Europe's largest river systems, the River Rhine, provides a unique geoscientific data set with the potential of bridging the gap between glaciated alpine areas and the inland ice-sheet advances of Northern Europe (WESTERHOFF 2008). The Upper Rhine Graben extends approximately 300 km from Basel (Switzerland) to Frankfurt (Germany) and is 35-45 km wide on average. This graben is a north-northeast-trending rift of Tertiary age (ELLWANGER et al. 2005). As a subsidence structure it forms an element of the Oligocene and Neogene rifting of the Upper Rhine Graben, representing 40 Ma of active graben tectonics (BEHRMANN et al. 2003). The Oberrhein (Upper Rhine) Valley, as a graben structure, forms part of the rifting system that began to develop during the mid-Tertiary (PREUSSER 2008). During the Quaternary, the subsiding part of the northern Upper Rhine Graben acted as a distal and final accommodation space for coarser alpine material (ELLWANGER et al. 2005).

Rhine sediments have recorded changes in both climate and tectonic activity (PREUSSER, 2008). During the Pliocene-Quaternary, the major subsidence centre shifted towards the eastern part of the graben (Heidelberg Basin), with a zone of maximum subsidence located in the central-eastern part of the basin, around the city of Heidelberg (ELLWANGER et al. 2005). The Pliocene-Quaternary infill of the Heidelberg Basin was mainly deposited by the River Rhine. The most distal signals of alpine climate dynamics associated with the major events of alpine glaciation can still be identified as sediment bodies within the Pleistocene succession. They are embedded in relatively fine alpine material and coarser local material. Coarser layers are also present, which are related to sediment input from the River Neckar (ELLWANGER et al. 2005). Towards the north, the character of the graben sediments change as a result of sorting processes during fluvial transport and admixture with local material derived from the graben margins. In the northern part of the Upper Rhine Graben the graben sediments are generally finer grained, better sorted and mixed with local sediment input from the graben margins (HAGEDORN & BOENIGK 2008).

1.2 Boreholes

Recently, numerous boreholes have been sunk to acquire new data for reinterpreting the geology of the northern Upper Rhine Graben. These research boreholes are at Heidelberg, Viernheim and Ludwigshafen-Parkinsel (hereinafter called Ludwigshafen for short); shallower local boreholes are located at Pfungstadt, Stadtwerke Viernheim and Hüttenfeld (Figure 1 and Table 1). The borehole at Viernheim documents the conditions at the centre of the basin and those in Ludwigshafen and Heidelberg the western and eastern margins of the basin facies. Ludwigshafen and Viernheim represent the succession of Rhine sediments, but both also include signals from non-rhine sedimentation: small rivers from Pfälzerwald in Ludwigshafen, Neckar sediments in Viernheim. The borehole in Pfungstadt is located at the northern margin of the Heidelberg Basin.

The most significant parameters of the investigated sites are given in Table 1. The geological surveys of Hessen, Baden-Württemberg and Rheinland Pfalz, respectively, are in charge of the investigated boreholes. The drilling depth varies significantly between the sites: the deepest boreholes are at Viernheim and Ludwigshafen (350 m and 300 m respectively) and the shallowest at Hüttenfeld (99 m). Overall core recovery is very high (81-99 %). The only exception is the borehole at Hüttenfeld, where only cuttings were analysed and documented. The depth reached by downhole measurements differs from the total depth due to borehole and technical problems.

The position of the Pliocene/Pleistocene boundary within these deposits, as well as the entire stratigraphy of the Upper Rhine Graben, is rather controversial (cf. ELLWANGER et al. 1995; FETZER et al. 1995; GIBBARD 2004; GIBBARD et al. 2005; CLAGUE 2006). The boundary

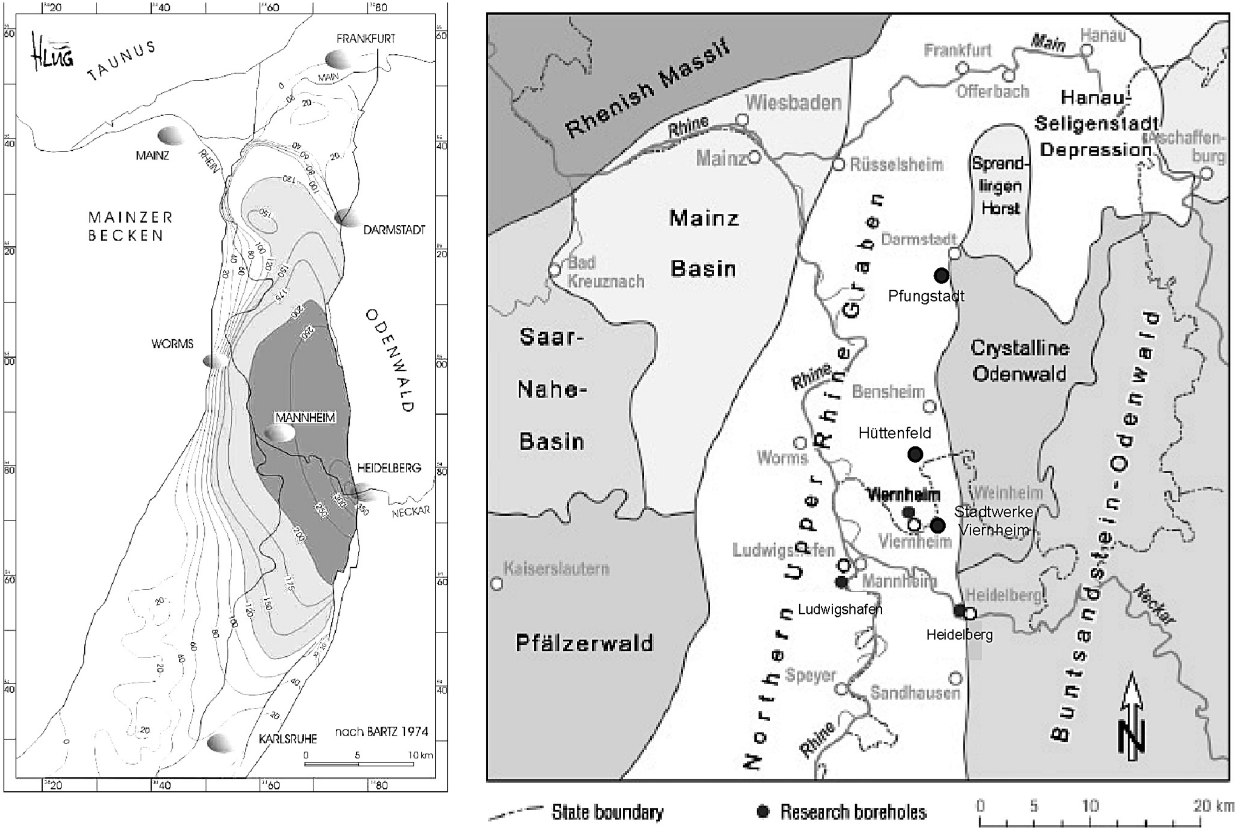

Fig. 1: Location of drill sites in the Heidelberg Basin. The main geological areas (Upper Rhine Graben, Odenwald, Pfälzerwald) and the main rivers (Rhine and Neckar) are marked (after HOSELMANN 2008). The small rectangle (left) comprises the sediment thicknesses of Quaternary age in the northern Upper Rhine Graben (after BARTZ 1974).

Abb. 1: Lage der Bohrlokationen im Heidelberger Becken (rechts). Die wichtigsten geologischen Gebiete (Oberrheingraben, Odenwald, Pfälzerwald) und die wichtigsten Flüsse (Rhein und Neckar) sind markiert (nach HOSELMANN 2008). Das Rechteck (links) enthält eine Darstellung der Sedimentmächtigkeit im Quartär im nördlichen Oberrheingraben (nach BARTZ 1974).

Table 1: Basic parameters of the investigated boreholes.

Tab. 1: Grundlegende Parameter der untersuchten Bohrungen.

	Pfungstadt	Hüttenfeld	Viernheim	Stadtwerke Viernheim	Heidelberg	Ludwigs-hafen
Responsible operating institution	Geological Survey (HLUG) Hessen	Geological Survey (HLUG) Hessen	Geological Survey (HLUG) Hessen	Geological Survey (HLUG) Hessen	Geological Survey (LGRB) Baden-Württemberg	Geological Survey (LGB-RLP) Rheinland-Pfalz
Drilling depth	200 m	99 m	350 m	110 m	180 m	300 m
Core recovery	98 %	Drill cuttings	97 %	99 %	81 %	99 %
Basis of Quaternary	At 132 m	Not recovered	At 225 m	Not recovered	Not recovered	At 177 m
Downhole logging	To 180 m	To 75 m, only GR	To 238 m	To 108 m, only GR	To 180 m	To 300 m, only GR

between Pliocene and Quaternary strata has been defined by the first occurrence of alpine input into the graben as indicated by the carbonate content within the sediments, as well as by the changing distribution of heavy minerals. The Pliocene sediments in the graben zone are predominantly fine-grained. Sandy clays alternate with fine to medium sands and some peat layers. Gravel layers occur only sporadically (HAGEDORN & BOENIGK 2008).

2 Methods

2.1 Downhole Logging

In the majority of boreholes downhole logging was conducted by the Leibniz Institute for Applied Geophysics (LIAG), Hannover; an exception is Hüttenfeld, where downhole logging was performed by the Geological Survey of Hessen (HLUG). The number of measured geophysical parameters at each site differs significantly: the most complete borehole measurement data sets were obtained at the Heidelberg and Viernheim sites, but Pfungstadt comprises a slightly reduced number of downhole measurements. At the Ludwigshafen, Stadtwerke Viernheim and Hüttenfeld sites only gamma ray logs (GR) were run.

The downhole logging in Heidelberg, Viernheim and Pfungstadt was conducted in several sections because of problems within these less lithified sediments during drilling. This means that up to five logging campaigns were necessary to complete downhole logging. The borehole diameter generally decreases in stages (e.g. from 244 mm to 200 mm to 150 mm) with increasing depth. The steps coincide with each logging campaign.

The downhole measurements can be differentiated into radioactive methods (density, neutron porosity, spectral gamma ray including gamma ray, potassium, thorium and uranium); acoustic methods (sonic velocity and acoustic borehole televiewer); electrical methods (dual laterolog resistivity, dipmeter); magnetic methods (magnetic susceptibility); and other methods (borehole diameter, temperature and salt content of the drilling mud).

Only those logs yielding information on the physical properties of the sediments, in particular on their grain size, were utilised for further

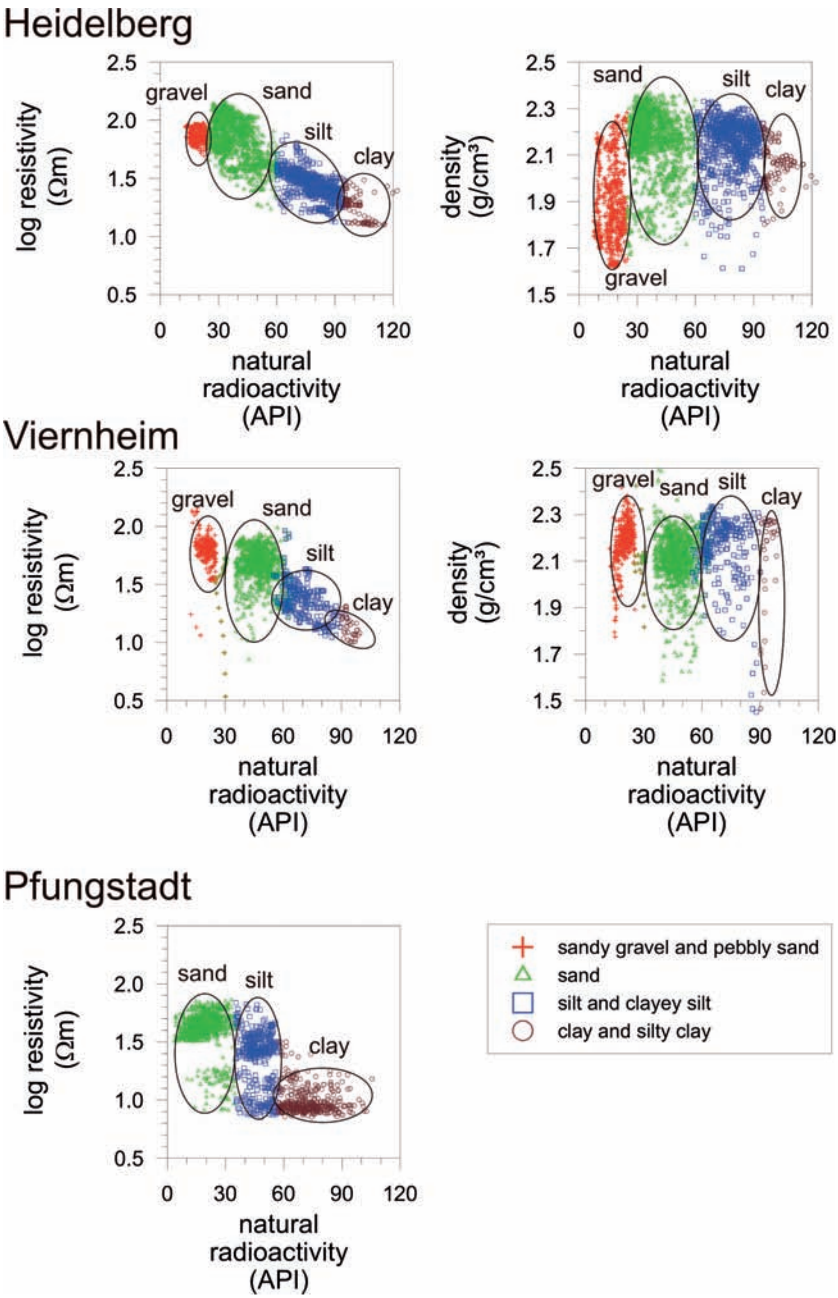

Fig. 2: Crossplots of the parameters natural radioactivity vs. resistivity and vs. bulk density for the drill sites Heidelberg, Viernheim and Pfungstadt. The four lithologies differentiated from the cores (sandy gravel; pebbly sand; sand, silt and clayey silt; clay and silty clay) are marked.

Abb. 2: Crossplots der Parameter natürliche Radioaktivität gegen Widerstand bzw. natürliche Radioaktivität gegen Dichte für die Bohrlokationen Heidelberg, Viernheim und Pfungstadt. Darin eingetragen ist die Differenzierung der vier Lithologien der Kerne (sandiger Kies und kiesiger Sand, Sand, Schluff und toniger Schluff sowie Ton und schluffiger Ton).

interpretation. These logs are GR, density, neutron porosity, resistivity, susceptibility, and caliper (borehole diameter). The caliper reflects the actual borehole diameter during logging as compared to the drilling diameter. Any sections with high differences in borehole diameter must be interpreted with caution. The neutron porosity log measures only relative porosity values; no absolute porosity values can be given. Therefore, the unit a.u. is used below.

2.2 Physical Properties

The main objective of analysing physical properties is to characterise each lithology by its specific physical properties. For better comparison the mean value and the standard deviation for each lithology has been calculated (Table 2 and Appendix). The log data sets were corrected prior to interpretation; this includes deleting erroneous and negative values. Those sections preferably with homogeneous lithology as determined by core descriptions (HOSELMANN 2008; WEIDENFELLER & KNIPPING 2008) are then selected and corrected using crossplots. Cross-plotting logs is usually done to quantify lithology and empirical relationships often become evident (RIDER, 1996). Finally, the physical properties of each lithology are calculated from the most prominent downhole logs, which are GR, density, porosity, resistivity (far) and susceptibility.

2.3 Hole-to-hole Correlation

Changes in sediment thickness, and therefore in sediment input, can be quantified by hole-to-hole correlation. This method comprises the synoptical comparison and connection of similar characteristic peaks and downhole log trends from adjacent sites. The correlation was performed using several logs (such as GR, susceptibility, porosity, density and resistivity), but most logs, except the GR log, were not measured at all sites and/or data variation is high. The correlation was therefore carried out on the GR log (Figures 3, 4 and 5), because of its low data scatter and characteristic log trends. RIDER (1996) pointed out that the GR log is used for correlation, because the 'character' of the gamma ray log is repeatable, is not affected by compaction with depth, and gives some indication of lithology.

2.4 Cluster Analysis

The lithologies and resultant possible sediment provenances were determined using the statistical method of cluster analysis (Ward method of complete hierarchical linkage, Figure 5). The WINSTAT Statistic for Windows (Version 3.1) software application was employed for this purpose.
Cluster analysis is a multivariate statistical technique, which assesses the similarities between units based on the occurrence or absence of specific components within them. This analysis creates homogeneous (members are similar to one another) groups of variables, the clusters. The elements in a cluster have relatively small distances from each other and relatively larger distances from elements outside a cluster (DAVIS 1986; BACKHAUS et al. 1996). Cluster analysis differentiates groups characterised by their physical properties. The number of clusters is determined using a tree-like structure, the dendrogram, which visualises the similarity of clusters (MOLINE et al. 1992, FRICKE & SCHÖN 1999). The dendrogram is cut horizontally at any level to create groups, which are compared to core data, and the most appropriate grouping level is chosen (RIDER 1996).
The cluster analysis is performed for four locations simultaneously, allowing a comparison of the resulting clusters between the drill sites. The maximum number of parameters used for calculating the clusters in Heidelberg and Viernheim is six (Table 2). However, the number of logging parameters is reduced at the two other locations: in Pfungstadt four parameters were measured and in Ludwigshafen only one. Cluster analysis was not performed for the Hüttenfeld and Stadtwerke Viernheim boreholes, because of an insufficient number of measured geophysical parameters.

Table 2: Overview of the logged parameters at each drill site. x: this parameter was logged at this site. -: this parameter was not logged.

Tab. 2: Überblick über die gemessenen Parameter an jeder Bohrlokation. x: der Parameter wurde an dieser Bohrlokation gemessen. -: der Parameter wurde nicht gemessen.

Drill site	SGR (API)	Density (g/cm³)	Neutron porosity (a.u.)	Resistivity (Ωm)	Suscepti-bility (10^{-4} SI)	Borehole diameter (mm)
Pfungstadt	x	-	x	-	x	x
Viernheim	x	x	x	x	x	x
Ludwigshafen	x	-	-	-	-	-
Heidelberg	x	x	x	x	x	x

3 Results

3.1 Physical Properties

3.1.1 Crossplots

The crossplots of the most significant parameters characterising the physical properties of the cored lithologies are described (Figure 2): the most useful logs for this purpose are GR, resistivity, and density in Heidelberg and Viernheim, and GR and resistivity in Pfungstadt. The other locations did not use these logs and, hence, crossplots cannot be plotted. Four groups of lithologies are differentiated based on the description of core lithologies: (1) sandy gravel and pebbly sand, (2) sand, (3) silt and clayey silt and (4) clay and silty clay.

The natural radioactivity (GR) vs. resistivity crossplots from Heidelberg, Viernheim and Pfungstadt (Figure 2, left column) are compared. The crossplots of the three locations show almost the same log trends: a strong negative correlation between GR and log resistivity. There, (a) sandy gravel and pebbly sand and (b) sand are characterised by low GR values (0-55 API) and high log resistivity values (0.8-2.3 Ωm). However, the log resistivity values of sandy gravel and pebbly sand differ between boreholes: in Heidelberg the values are slightly higher (1.3-2.3 Ωm) than in Viernheim (1.1-2.1 Ωm) and considerably higher than in Pfungstadt (0.8-1.9 Ωm). At all sites (a) silt and clayey silt and (b) clay and silty clay are characterised by high GR values (55-130 API) and low log resistivity values (0.8-1.8 Ωm). It is important to note that in Pfungstadt the downhole logs were measured within the liner and, as a result, the downhole logs, especially the GR values, are significantly lower. If this is corrected, the boundary values for each lithology are also corrected. However, the clay resistivity values for Pfungstadt are much lower than at the other sites.

The crossplots GR vs. density for Heidelberg and Viernheim (Figure 2, right column) are plotted. In Heidelberg, the density data differ between the sandy gravel and pebbly sand (1.6-2.2 g/cm³) and the sand, silt and clayey silt, and clay and silty clay lithologies (1.8-2.4 g/cm³). In contrast, almost all Viernheim lithologies display similar density data (1.8-2.4 g/cm³). An exception is sandy gravel and pebbly sand, which are characterised by slightly enhanced values (1.9-2.4 g/cm³). Unfortunately, no density data were recorded in Pfungstadt. One possible reason why sandy gravel and pebbly sand display lower density values in Heidelberg than in Viernheim may be a lesser degree of compaction in Heidelberg due to rapid sedimentation from the River Neckar. This conclusion coincides

Appendix: Physical properties (mean value and standard deviation) of the six investigated boreholes within the Heidelberg basin. The boreholes are sorted according to distance from the margin towards the centre of the Heidelberg Basin. The number of data points varies as a function of the logging parameter.

Pfungstadt	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	0	957-1000	197-522	420-428
GR (API)	-	20±7	47±6	72±10
Log resistivity (Ωm)	-	1.61±0.16	1.36±0.24	0.98±0.09
Log susceptibility (10^{-4} SI)	-	0.65±0.06	0.62±0.05	0.63±0.06

Ludwigshafen	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	828	4108	263	806
GR (API)	20±3	39±8	68±6	102±9

Hüttenfeld	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	737	450	163	47
GR (API)	24±5	37±4	59±6	77±7

Viernheim	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	325-466	1114-1165	261-324	38-110
GR (API)	20±3	47±7	70±8	109±15
Density (g/cm³)	2.20±0.12	2.12±0.13	2.16±0.14	2.11±0.23
Neutron porosity (a.u.)	35±11	38±11	42±12	46±14
Log resistivity (Ωm)	1.75±0.29	1.60±0.36	1.37±0.16	1.15±0.09
Log susceptibility (10^{-4} SI)	0.65±0.26	0.80±0.43	0.87±0.67	0.71±0.45

Stadtwerke Viernheim	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	774	677	552	132
GR (API)	27±5	42±4	58±5	77±6

Heidelberg	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	409-1034	1584-1661	775-808	99-110
GR (API)	15±5	38±9	78±9	102±6
Density (g/cm³)	1.90±0.17	2.16±0.13	2.14±0.11	2.06±0.09
Neutron porosity (a.u.)	41±18	33±5	38±5	43±8
Log resistivity (Ωm)	1.87±0.06	1.86±0.19	1.44±0.11	1.25±0.11
Log susceptibility (10^{-4} SI)	0.66±0.05	0.57±0.06	0.65±0.11	0.67±0.06

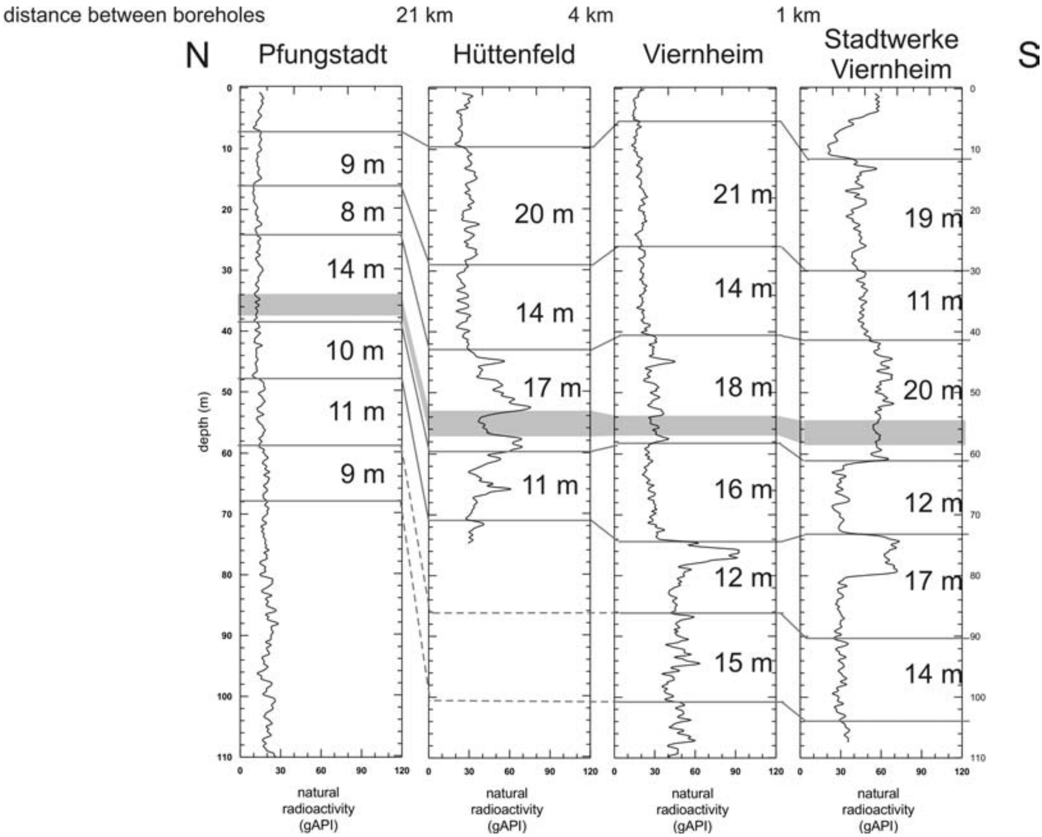

Fig. 3: Hole-to-hole correlation using the natural radioactivity log (smoothed) of the drill sites around Viernheim (Viernheim, Stadtwerke Viernheim and Hüttenfeld) and the Pfungstadt borehole. The grey horizontal lines mark the sediment package, characterised by its specific log trends and peaks. The grey boxes mark the detailed correlation of this randomly selected sediment package.

Abb. 3: Bohrloch-Bohrloch Korrelation unter Verwendung des Logs der natürlichen Radioaktivität (geglättet) der Bohrlokationen um Viernheim (Viernheim, Stadtwerke Viernheim und Hüttenfeld) sowie Pfungstadt. Die graue horizontale Linie markiert das Sedimentpaket, das charakterisiert ist durch seine besonderen Logtrends und Spitzen. Die grauen Kästchen markieren die detaillierte Korrelation dieser zufällig ausgesuchten Sedimentpakete.

with the highest sediment thickness at the basin centre. Another reason may be the mineralogy of the sediments at the different drill sites.

Comparing the results of both crossplots shows that the GR vs. resistivity crossplot implies that the fine-grained sediments are characterised by low resistivity values, which suggests high conductivity possibly caused by high water content, salinity and/or porosity. In the GR vs. density crossplot the coarser-grained sediments are characterised by both low and high density values and the finer-grained ones by high density values. This suggests that the high density values in fine-grained sediments may be caused by mineralogy and/or a higher degree of compaction.

3.1.2 Statistics of Physical Properties

The physical properties of the Upper Rhine

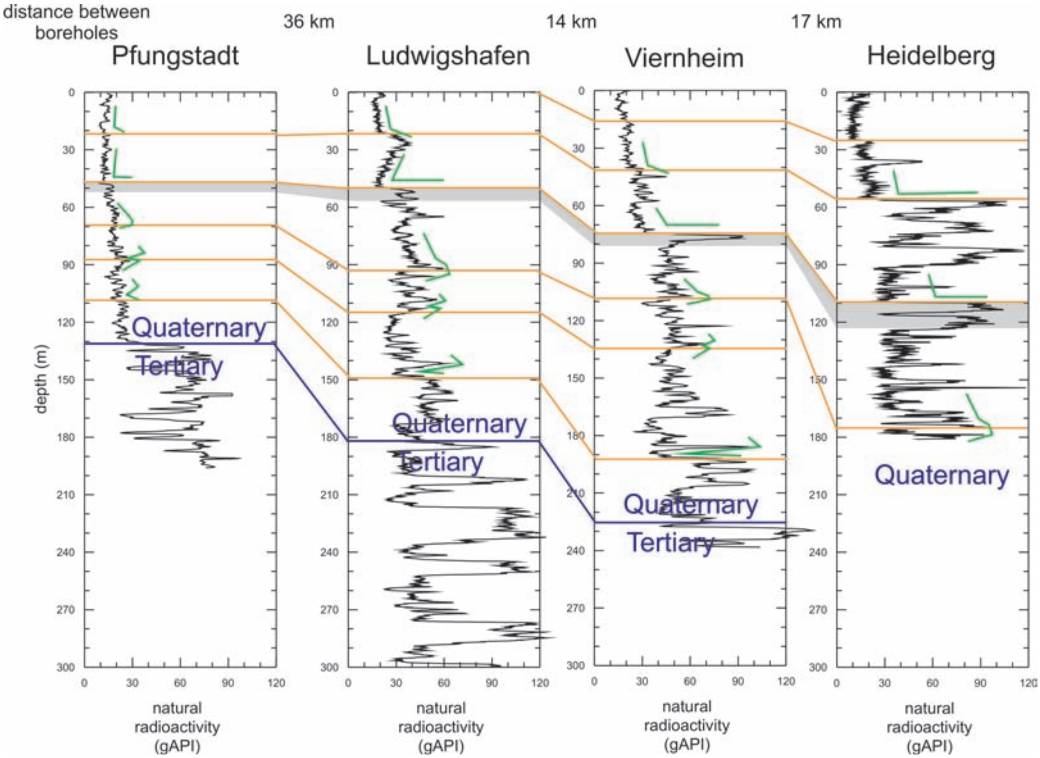

Fig. 4: Hole-to-hole correlation using the GR log from the drill sites within the Heidelberg Basin (Pfungstadt, Ludwigshafen, Viernheim, and Heidelberg). The lowermost blue horizontal lines mark the Pliocene-Pleistocene boundary as described in the cores. The red horizontal lines mark the sediment package, characterised by specific log trends (marked with vertical line) and peaks. The green lines mark the characteristic log trends. The grey boxes mark the detailed correlation of one randomly selected sediment package.

Abb. 4: Bohrloch-Bohrloch Korrelation unter Verwendung des GR Logs der Bohrlokationen im Heidelberger Becken (Pfungstadt, Ludwigshafen, Viernheim und Heidelberg). Die unterste blaue, horizontale Linie markiert die Pliozän-Pleistozän Grenze wie sie in den Kernen beschrieben wurde. Die anderen roten, horizontalen Linien markieren jeweils das Sedimentpaket, das charakterisiert ist durch seine besonderen Logtrends (markiert mit vertikaler Linie) und Spitzen. Die grünen Linien markieren die charakteristischen Logtrends. Die grauen Kästchen markieren die detaillierte Korrelation dieser zufällig ausgesuchten Sedimentpakete.

Graben were computed to determine both their characteristics and their changes according to location within the Heidelberg Basin (see Appendix). The physical properties are described using Viernheim as an example (Table 3). Principally, natural radioactivity reflects the grain size: the higher the natural radioactivity values, the higher the clay content of the sediment. The density and log resistivity values decrease and the neutron porosity values increase with increasing clay content (from sandy gravel to clay). Again, this may imply a decreasing degree of compaction from the coarser-grained to the finer-grained sediments. The log susceptibility values vary with grain size, because this parameter mainly reflects an overall change in sediment input.

A number of important trends are observed by comparing the physical properties of all lithologies within the Heidelberg Basin (see Appendix). Overall, it must be kept in mind that the lithologies were defined for each site separately. This leads to more or less significant differences in GR values between

Table 3: Physical properties of the Viernheim sediments derived from logging data. The number of data points is given for quality control.

Tab. 3: Die physikalischen Eigenschaften der Sedimente in Viernheim, die aus den Bohrlochmessungen abgeleitet wurden. Die Anzahl der Messdaten wird zur Qualitätskontrolle angegeben.

Viernheim	Sandy gravel, pebbly sand	Sand	Silt, clayey silt	Clay, silty clay
Number of data points	325-466	1114-1165	261-324	38-110
Natural radioactivity (API)	20±3	47±7	70±8	109±15
Density (g/cm³)	2.20±0.12	2.12±0.13	2.16±0.14	2.11±0.23
Neutron porosity (a.u.)	35±11	38±11	42±12	46±14
Log resistivity (Ωm)	1.75±0.29	1.60±0.36	1.37±0.16	1.15±0.09
Log susceptibility (10^{-4} SI)	0.65±0.26	0.80±0.43	0.87±0.67	0.71±0.45

the boreholes and the composition of each lithology varies among the drill sites. Sand is taken as an example: varying GR values at the different drill sites imply different amounts of fine-, medium- and coarse-grained sand and a varying amount of clay within the sediment matrix. This is valid for all four lithologies. However, the bulk density values of all drill sites are comparable, but the GR values differ significantly between Heidelberg and Viernheim. Reasons may be different mineralogical compositions caused by different sediment provenances.

3.1.3 Sediment Thickness

The crossplots facilitate a differentiation of lithologies. The thickness of the sediment in each lithology is determined from this (Table 4). The main objective is to quantify the changes in sediment composition from margin to centre in the Heidelberg Basin and from south to north in the Upper Rhine Graben. In Pfungstadt (at the northern margin of the basin) the drilled and logged sediments are mainly composed of sand (sediment thickness 100.0 m). Pfungstadt is located furthest north of all boreholes in the Upper Rhine Graben. Thus, input from the Odenwald is high and less influenced by the River Rhine due to its distance from the Rhine Graben. This borehole contains the highest amount of clay and silty clay (45 m), which may be a result of its location at the northern margin of the basin with its fine-grained sediment input. In comparison, there are only small differences to the other drill site in the basin margin at Ludwigshafen. The lithology with the largest sediment thickness is sand (205 m), and the smallest is silt and clayey silt (13 m). Finally, the borehole at Heidelberg (at the centre of the Heidelberg Basin) is characterised by very thick sandy sediments (82 m) and much lesser clay and silty clay (4 m). These observations reflect the input of coarser-grained sediments from the River Neckar and almost no influence by the River Rhine.

Overall, it must be kept in mind that the total drilling depth and total logging depths differ locally due to borehole collapse. The most significant example is Hüttenfeld, where the total drilling depth amounts to 99 m and, in contrast, the total logging depth is only 75 m. This leads to incomplete analysis of lithologic composition, which underestimates the less compacted lithologies such as sand and gravel.

Table 4: Overview of sediment thicknesses in all boreholes differentiated according to the four cored lithologies. The boreholes are sorted according to distance from the margin to the centre of the Heidelberg Basin. The bold numbers are the highest and lowest values of each drill site, respectively.

Tab. 4: Überblick über die Sedimentmächtigkeiten an allen Bohrlokationen, die entsprechend den vier in den Kernen erbohrten Lithologien differenziert wurden. Die Bohrlokationen sind nach ihrer Entfernung vom Beckenrand bis zum Zentrum des Heidelberger Beckens sortiert. Die fett gedruckten Zahlen stellen die jeweils höchsten und tiefsten Werte für jede Bohrlokation dar.

		Sediment thickness (m)			
	Logging depth (m)	Sandy gravel and pebbly sand	Sand	Silt and clayey silt	Clay and silty clay
Pfungstadt	198	**0**	**100**	53	45
Ludwigshafen	300	41	**205**	**13**	40
Hüttenfeld	75	**38**	24	9	**4**
Viernheim	238	53	**133**	38	15
Stadtwerke Viernheim	108	**39**	34	28	**6.9**
Heidelberg	175	50	**82**	39	**4.1**

3.2 Sediment Provenance

3.2.1 Viernheim

3.2.1.1 Hole-to-hole Correlation

Although Hüttenfeld and Pfungstadt are separated by 21 km, the resulting correlation between all four drill sites around Viernheim, as determined by hole-to-hole correlation, is good (Figure 3). The thicknesses of the line-marked sediment sections at the drill sites around Viernheim do not vary significantly, but decrease slightly towards Pfungstadt.

As an example, one randomly selected sediment package is picked and marked grey (Figure 3). Surprisingly, the thickness of this sediment section increases from Stadtwerke Viernheim and Viernheim to Hüttenfeld and Pfungstadt. The selected sediment section is composed of sand to silt and clayey silt and is about 2 m thick in Viernheim and Stadtwerke Viernheim. This increases to 2.5 m in Hüttenfeld, which may be a result of local sediment accumulation. On the other hand, the two drill sites around Viernheim (Viernheim and Stadtwerke Viernheim) may be influenced by erosion or sediment compaction. The sediment thickness in Pfungstadt decreases slightly to 2 m, due to different, possibly local sediment input from Odenwald.

3.2.1.2 Cluster Analysis

The cluster analysis for the drill sites around Viernheim could not be performed due to the absence of several geophysical parameters measured downhole.

3.2.2 Heidelberg Basin

3.2.2.1 Hole-to-hole Correlation

Overall, there is good correlation between all four drill sites determined from hole-to-hole measurements (Figure 4), despite the large distances between the investigated sites (36 km between Pfungstadt and Ludwigshafen). As anticipated, the thickness of correlated sediment

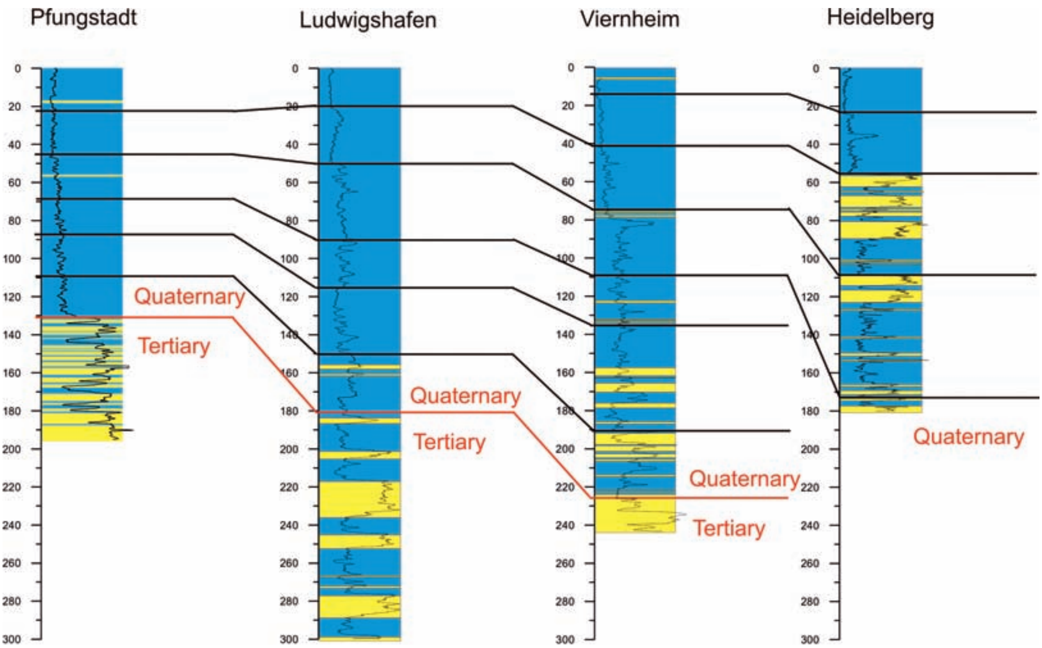

Fig. 5: Results of the cluster analysis of the Ludwigshafen, Viernheim, Pfungstadt, and Heidelberg boreholes. The characteristic GR log and the Pliocene-Pleistocene boundary for each site are plotted.

Abb. 5: Ergebnisse der Clusteranalyse der Bohrlokationen Ludwigshafen, Viernheim, Pfungstadt und Heidelberg. Darin sind das charakteristische GR Log und die Pliozän-Pleistozän Grenze für jede Bohrlokation dargestellt.

layers is greatest in Heidelberg, which is located in the subsidence centre of the Heidelberg Basin, and lowest in Pfungstadt located at the northern margin of the basin.

Again, one sediment package is chosen at random to determine the changes in sediment provenance (Figure 4). The following description of the sediment package is based on a profile from the two margins of the basin (Pfungstadt and Ludwigshafen) to its centre (Heidelberg). The log trends and the thickness of the chosen sediment package are quite similar in Pfungstadt and Ludwigshafen (sediment composition: sandy gravel and pebbly sand). In Viernheim, the sediments are fine-grained in the upper part and coarse-grained in the lower part. Thus, additional fine-grained input did occur. Finally, in Heidelberg, the sediment composition changes again: the sediments are mainly composed of clay and only small amounts of sand occur. Surprisingly, the log characteristics are quite similar to the curve trends at Ludwigshafen, but with enhanced clay content. Sediment transport to Viernheim is influenced by a different sediment provenance (such as the River Rhine) or is blocked by a local sediment barrier.

3.2.2.2 Cluster Analysis

The clusters are computed for each drill site, separately defining the number of clusters (Figure 5). Overall, this number was defined as two, because the other clusters contained only a few data points or reflect erroneous values (e.g., at the top or the bottom of the borehole). The determined clusters were interpreted as different lithologies reflecting two different sediment provenances: The first cluster (dark coloured) with low GR (34±13 API), high log resistivity (1.60±0.33 Ωm) and low log susceptibility ($0.67 \pm 0.21 \ 10^{-4}$ SI) values reflects sediments rich in sandy gravel and pebbly sand to sand, which probably originate from the River Neckar (proximal deposition from Odenwald). The second cluster (light coloured) with high GR (81±20 API), low log resistivity (1.29±0.45 Ωm) and high log susceptibility (0.77±0.52 10^{-4} SI) values mainly contains sediments rich in clay, which were probably deposited from the River Rhine (distal deposition from the Alps, Black Forest and Vogues). The other parameters (density, borehole diameter, and neutron porosity) have similar values for both clusters. Transferring the hole-to-hole correlation to the results of the cluster analysis shows clear differences in sediment provenances. These observations lead to the assumption that overall sediment depositions are similar, but differ in detail influenced by two different sediment provenances River Neckar (Cluster 1) and River Rhine (Cluster 2).

4 Conclusions and Discussion

The interpretation of downhole logs leads to the following conclusions: the physical properties of sediments derived from logs and cores can be quantified and the results compared. Four groups of lithologies can be differentiated using the natural radioactivity (GR) vs. resistivity and GR vs. density crossplots: (1) sandy gravel and pebbly sand, (2) sand, (3) silt and clayey silt and (4) clay and silty clay. The results of the GR vs. resistivity crossplots imply high conductivity possibly caused by high water content, salinity and/or porosity. In the GR vs. density crossplot, the coarser-grained sediments are characterised by both low and high density values and the finer-grained sediments (silt, clayey silt, clay and silty clay) by high density values. This suggests that the high density values in fine-grained sediments may be caused by mineralogy and/or a higher degree of compaction.

Interpretation of the hole-to-hole correlation displays a coincidence of sediment provenances around Viernheim (close to the centre of the Heidelberg Basin) and only small changes towards Pfungstadt (located at the northern margin of the basin). Furthermore, this correlation shows the anticipated changes in sediment layer thickness from Pfungstadt (smallest thickness) to Heidelberg (greatest thickness at the basin centre). Additionally, the statistical method of cluster analysis confirms two main sediment provenances interpreted as deposits from the Rivers Rhine and Neckar. However, the results of the hole-to-hole correlation and the cluster analysis differ. This implies different contributions of a single sediment package to one of the two sediment provenances. The problem posed here is that both methods are based on assumptions and more interpretation is necessary: hole-to-hole correlation is a visual method, very detailed and based on the assumption that the GR log is the most significant log, because it mainly describes the sediment composition. On the other hand, the cluster analysis needs a predefined number of clusters and must be interpreted carefully.

More investigations are required to determine absolute ages in the investigated boreholes in order to confirm and/or critically test our visual and statistics-based hole-to-hole correlation and the interpreted sediment provenances. Sedimentological interpretations should be incorporated in our small-scale observations and expansion to a basin-scale analysis should follow.

Additionally, data acquired after deepening of the Heidelberg drill site in spring 2008 to an end depth of 500 m should be integrated in further studies, which are important in terms of the Tertiary-Quaternary boundary and the changes in sediment thickness at the drill sites.

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Pleistocene molluscs from research boreholes in the Heidelberg Basin

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Abstract: Cores cut in the research boreholes at Viernheim and Parkinsel P34 and P35 in Ludwigshafen were analysed to investigate their fossil content, and particularly the remains of molluscs. The selected material was suitable for reconstructing the palaeoclimatic conditions and simplifies the chronostratigraphic classification of individual beds. Two mollusc species and one rodent species from the Lower Pleistocene (Lower Biharium) were identified in the northern Upper Rhine Graben for the first time (in the Viernheim borehole). The fossils from the Lower Pleistocene sections of the Viernheim borehole are clearly related to the Uhlenberg fauna from Bavarian Swabia dated as Upper Villanium/Tegelen.

[Pleistozäne Mollusken aus Forschungsbohrungen im Heidelberger Becken]

Kurzfassung: Bohrkerne der Forschungsbohrungen Viernheim und Parkinsel P34 und P35 aus Ludwigshafen wurden auf ihren fossilen Inhalt, besonders auf Molluskenreste, untersucht. Das ausgelesene Material ist geeignet die paläoklimatischen Verhältnisse zu rekonstruieren und erleichtert die chronostratigraphische Einstufung einzelner Schichten. Zwei Molluskenarten und eine Nagetierart wurden erstmalig aus dem Altpleistozän (Altbiharium) der Bohrung Viernheim für den nördlichen Oberrheingraben nachgewiesen. Die aus den altpleistozänen Abschnitten der Bohrung Viernheim vorliegenden Fossilien weisen deutliche Beziehungen zu der in das Obere Villanium/Tegelen datierten Uhlenberg-Fauna aus Bayerisch-Schwaben auf.

Keywords: Upper Rhine Graben, Quaternary, Pleistocene, Arvicolidae, Mollusca, Stylommatophora, Pupilloidea, Gastrocoptinae

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1 Introduction

The mollusc fauna in the Upper Rhine Graben is very important for palaeoclimatology because most of the mollusc species are still present today in the flood plains of large valleys, and their habitats and lifestyles are known. They provide information on hydrological and climatic change, and landscape history, and can therefore provide "valuable pieces in the dating puzzle" (Engesser & Münzing 1991). Most endemic mollusc species already colonised our landscapes in the Upper Pliocene. In addition, the northern Upper Rhine Graben in the Pleistocene lay in an optimum development zone according to the description by Ložek (1969) of the climatically favourable zones of the Czech Republic and Southwest Germany. During the interglacials, the climate here meant that the mollusc fauna was much more habitat sensitive than that of northern Central Europe. During the periods of glaciation, the glacial ice did not extend into the Upper Rhine Graben area, which meant that the area had favourable conditions for the survival of animals, as well as molluscs. Loess steppes exist in the Upper Rhine area during the high glacial periods.

2 Research boreholes in the Heidelberg basin

2.1 Fossil material and depositional conditions

The thanatocoenosis of molluscs from a core only reflects a small piece of the overall landscape complex. It is therefore also important to look at the sediments in more detail. Fossils are often found in the argillaceous layers of the "Zwischenhorizonte" (intermediate horizons) as well as in the fine and medium-grained sands of the "Kieslager" (gravel beds). The grey sand horizons of the "Rhenish Facies" (Hoselmann 2008) in the Lower Quaternary may contain open steppe fauna of the glacials and interglacials. The coarser the sediment, the poorer the preservation of the mollusc shells. The coarser gravels also contain few species because they are formed during glacial conditions. An exception are the loess horizons which are, however, usually only found at the boundary to slope deposits. Loess horizons contain mollusc fauna which although species poor, contain characteristic high glacial species. These horizons are not found in the cores from the fluviatile Rhine Graben. However, molluscs do occur in some sandy beds, which indicate high glacial conditions. The work of Bartz (1959) is recommended for a short, though usually still valid subdivision of the Pleistocene in the northern Upper Rhine Graben, and for the description of the most important associated fossil localities – although the middle sandy sequence described in this paper is today classified as Middle Pleistocene (Engesser & Münzing 1991).

2.1.1 Condition of preservation of fossil molluscs

Complete gastropods and molluscs are only rarely preserved. This is possible in some of the clay lenses of the intermediate horizons as well as in a few hard "Terra Rossa beds" from Cromerian horizons. This also applies to small specimens in sand, finer gravel beds and flood sediments. In other cases, identification of species is based on the characteristic properties of the aperture armatures and the surface structures. The shells are sometimes corroded, polished or seriously fragmented by transport and the influence of water. We now know that the thickness of the shells does not provide any information on the climatic conditions: thick-shelled gastropods were also present during interglacials and are therefore not necessarily an indicator of a colder climate (Geissert 1967a).

2.1.2 The Oberer Zwischenhorizont (OZH)

The Oberer Zwischenhorizont (Upper Intermediate Horizon) is undoubtedly the most interesting level in all of the investigated boreholes because of the numerous mollusc remains and also because it contains sensitive interglacial species whose presence can be correlated with palynological analysis. Exceptions are the argillaceous peat beds from the low peat bogs of the Upper Pleistocene which mostly originated in periglacial periods. They are present in thin beds, e.g. in boreholes from around Darmstadt and Riedstadt (SCHWEISS 1988). At the west edge of the Rhine Graben, the minor thickness of the Obere Kieslager (Upper Gravel Horizon) of the OZH means that the OZH is already encountered at a depth of around 30 m. In addition, this OZH originated in the Middle Pleistocene as deduced from pollen analysis (KNIPPING 2004) and from the molluscs. The further to the east one looks at the Quaternary sequences, the thicker and more detailed they become. The Viernheim research borehole therefore includes several argillaceous intermediate horizons. The Lower Pleistocene in Viernheim is reached in the third, lower horizon. The Oberer Zwischenhorizont is characterised by beds of sandy, silty and argillaceous sediments. The thickness and nature of the OZH can fluctuate widely (ENGESSER & MÜNZING 1991).

2.1.3 The Pliocene clays

Because of the absence of molluscs, the Pliocene samples provided no results in the Ludwigshafen boreholes or in the Viernheim borehole. Only a few rare shell remains were found which could not be identified because of the frequent strong corrosion of the fragments. Plant residues were however frequently found. Only very rare molluscs have been found previously in boreholes within Pliocene sediments of the southern Rhine Graben. (GEISSERT 1964, 1967b, 1980; NORDSIECK 1974; SCHLICKUM & GEISSERT 1980; WEDEL unpublished).

2.2 The Ludwigshafen boreholes (Rheinland-Pfalz)

The filling of the Rhine Graben with Quaternary sediments increases considerably to the east towards the edge of the Odenwald, so that the

Fig. 1: *Perforatella bidentata* (GMELIN, 1788), Gernsheim C00-BK1 at 88.4 m.

Abb. 1: *Perforatella bidentata* (GMELIN, 1788), Gernsheim C00-BK1 bei 88,4 m.

Fig. 2: *Gastrocopta moravica oligodonta* (KROLOPP, 1979), Viernheim research borehole, 132.6-132.7 m.

Abb. 2: *Gastrocopta moravica oligodonta* (KROLOPP, 1979), Forschungsbohrung Viernheim, 132,6-132,7 m.

thickest Quaternary deposits are encountered around Heidelberg. The thickness is much thinner at the western margin of the Rhine Graben so that in borehole P35, the Tertiary boundary is already found at a depth of 183 m. The Quaternary is divided up into sequences of terraces built up by gravel horizons and intermediate horizons. Similar to palynological investigations, sampling concentrates on the dark, argillaceous intermediate horizons representing interglacial deposits.

2.2.1 Borehole P34

Borehole P34 (Ludwigshafen-Parkinsel, Tab. 1) has much less investigatable material than the other boreholes. The only malacological sample with any usable material comes from the first sample taken from the OZH at 21 m depth. The dark beds contain numerous mollusc remains. The high proportion of *Valvata cristata* (O. F. Müller, 1774) and *Gyraulus crista* (Linnaeus, 1758) indicate swampy stagnant water conditions on the flood plains. 98 per cent of the species found are water molluscs. Of the few terrestrial gastropods found, they are all of hydrophilic species with the exception of *Clausilia* fragments transported in by water, and *Aegopinella* sp.. The thanatocoenosis is very similar to that of early Holocene flood plains in which flood plain clay is formed and Tschernozems and para brown earths can develop to maturity (Ložek 1964). The terrestrial molluscs found in the samples are of climate-independent species and therefore often not very useful for determining the temperature fluctuations. *Vertigo substriata* (Jeffreys, 1833) and *Oxyloma elegans* (Risso, 1826) are typical swamp and peat bog species and not necessarily restricted to calcareous soils, although the charophytes present (calcalgae) indicate such an environment. Pollen analysis of the pollen from the Oberer

Fig. 3: *Gastrocopta n. sp.* from the Viernheim research borehole, 174.3-174.4 m.

Abb. 3: *Gastrocopta n. sp.* aus der Forschungsbohrung Viernheim, 174,3-174,4 m.

Fig. 4: *Parafossarulus crassitesta* (Brömme, 1883), Ludwigshafen Maudach A36 borehole, 27.5-28.0 m OZH.

Abb. 4: *Parafossarulus crassitesta* (Brömme, 1883), Bohrung Ludwigshafen Maudach A 36 27,5-28,0 m OZH.

Zwischenhorizont in P34 analysed by KNIPPING (2004) confirmed its attribution to the Cromerian Complex (interglacial III or IV). This also matches the results reported by RÄHLE (2005) and the author for the boreholes in Mannheim and Ludwigshafen described below.

2.2.2 Borehole P35

The Quaternary is divided up into sequences of terraces built up by gravel horizons and intermediate horizons, whereby the uppermost "Oberer Zwischenhorizont" of borehole P35 begins at 19 m and does not end until 34 m. 5 samples were taken from this zone. It is followed by an 8-metre-thick "Unteres Kieslager". This is underlain by sandy sequences containing organic material (peat) at six positions. Mollusc samples were extracted from 50-50.3 m and at 88.7 m. A "Unterer Zwischenhorizont" lies between 98 and 109 m. The "Unterer sandig-schluffigen Abfolgen" (Lower sandy-silty sequences) continue on to the Pliocene boundary. A sample from 178.9 m was selected from this zone. Another sample was collected in the Pliocene clays at 236.1 m in P35. Two additional samples from the Pliocene at 276.2 and 287.5-287.9 m were investigated from borehole P35a which was drilled directly adjacent to P35.

The most concentrated mollusc remains in borehole P35 are also found in the uppermost layer in the OZH at 21.9 m, and in the "Oberer sandige Folge" (Upper Sandy Suite) at 50 m. Both horizons contain gastropod fauna primarily belonging to interglacial species. The samples differ in the spectrum of species they contain. The sample at 21.9 m primarily contains terrestrial species pointing to the presence of a flood plain forest (*Perforatella bidentata*). The fauna from the sample at 50 m is aquatic consisting of stagnant plant-rich waters (*Gyraulus crista*, *Lymnaea stagnalis*, *Bathyom-*

Fig. 5: *Borysthenia naticina* (MENKE, 1845) from the Viernheim research borehole, 164.0-164.2 m.

Abb. 5: *Borysthenia naticina* (MENKE, 1845) Forschungsbohrung Viernheim, 164,0-164,2 m.

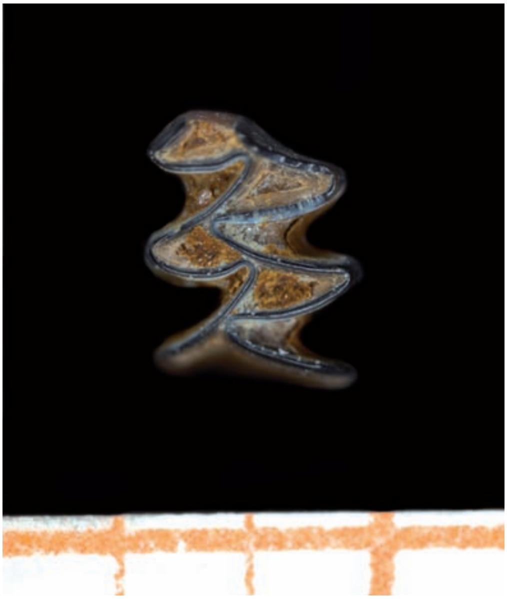

Fig. 6: Molar 2 of *Mimomys ostramosensis* (JANOSSY & VAN DER MEULEN, 1975) from the Lower Biharium in the Viernheim research borehole, 182.3-182.5 m.

Abb. 6: Molar 2 von *Mimomys ostramosensis* (JANOSSY & VAN DER MEULEN, 1975) aus dem unteren Biharium der Forschungsbohrung Viernheim, 182,3 -182,5 m *phalus contortus* and *Planorbarius corneus*) to slow flowing waters. Unfortunately, the material at 50 m has been compacted within a silty-sandy sediment which has become broken up as a result of elutriation. Some juvenile examples are still preserved. The composition of the thanatocoenosis at 50 m indicates the Mosbacher Sande 2 (Geissert 1970) by way of *Borysthenia naticina* (Menke, 1845) (Fig. 5), because these sands also contain this species.

The terrestrial molluscs from the sample at 21.9 m are mostly hydrophilic (e.g. *Vertigo substriata, Vallonia enniensis, Carychium minimum* as well as *Carychium tridentatum*). The sample from the OZH at approx. 21 m in borehole P34 also contains a rich mollusc fauna, although dominated in this case by freshwater species. Terrestrial snails typical of warmer conditions, as still found today under leaf mould in shady flood plain forests, are the waxy glass snails, e.g. *Aegopinella nitens* (Michaud, 1831).

The two completely preserved valves of the pea clam *Pisidium amnicum* (O. F. Müller, 1774) from 27.8 – 28.0 m are very interesting. This species occurs again at 178 m although it is primarily associated in the sample with species which tended to live in glacial, open landscapes. However, this mollusc is generally more frequent in interglacial deposits.

The molluscs in both boreholes indicate interglacial conditions. There is still some doubt, however, whether we are dealing here with the Cromerian or the Holsteinian interglacial because important type fossils are absent. The situation in the other boreholes described below is different because the molluscs in these boreholes can be confidently assigned to the Cromerian Complex.

2.3 Boreholes in Mannheim-Lindenhof (Baden-Württemberg) and Ludwigshafen – A36 Maudach (Rheinland-Pfalz)

The boreholes drilled in Mannheim-Lindenhof (Rähle 2005) and Ludwigshafen – A 36 Maudach (Wedel unpublished), are particularly interesting. They were drilled in the vicinity of the two boreholes described above and were sunk in advance of the research boreholes and investigated by LGB Rheinland-Pfalz. The boreholes contain notable fossil gastropod species from the Oberer Zwischenhorizont (Tab. 3). The first of these is *Clausilia rugosa antiquitatis* (Nordsieck, 1990). This form has been identified in the younger Tegelen up to the older Middle Pleistocene. It is replaced in the Middle Pleistocene by *Clausilia rugosa parvula* (Férrusac, 1807). The second interesting gastropod is *Parafossarulus crassitesta* (Brömme, 1885) (Fig. 4).

Two particularly well preserved examples with numerous characteristic opercula of this species were found in the Maudach borehole between 27 and 28 m depth. The genus *Parafossarulus* is no longer present in Europe (Gloer 2002). In addition, the boreholes in Mannheim and Ludwigshafen-Maudach also contained remains of *Azeca goodalli* (A. Férussac, 1821).

According to Rähle (2005), this "*crassitesta*-horizon" is not younger than Cromerian interglacial IV and not older than Cromarian interglacial III. This investigation looked at the Oberer Zwischenhorizont in eight different boreholes in Mannheim-Lindenhof, and specifically at the depth zone between 29 and 33 m. Analogous to Mannheim-Lindenhof, the Maudach borehole also contained tooth remains of early forms of the water vole *Arvicola terrestris* (Linne, 1758). The genus *Arvicola* appears in Central Europe at the earliest in Cromerian interglacial III (OIS 15) according to Koenigswald & van Kolfschoten (1996). The fauna encountered in Mannheim-Lindenhof is therefore of a very similar age to Mosbach 2 (Middle Mosbach) and Mauer, where *Arvicola* is also found (Rähle 2005). The results from other investigations of the OZH are also reported by Engesser & Münzing (1991) from boreholes that are also from the Mannheim area.

2.4 Viernheim research borehole (Hessen)

The conclusions drawn from the Viernheim borehole are that the three intermediate horizons encountered in the well reflect differentiated climatic conditions. Unlike the Ludwigshafen boreholes, the Oberer Zwischenhorizont (Section Xa according to Hoselmann 2008) is marked by climatically cooler species (Tab. 4). The second intermediate horizon from 89 m contains species preferring warmer conditions. This may possibly be the same horizon as in the Ludwigshafen-Mannheim area ("*crassitesta*" – horizon), although the type species is missing. The 5 m-thick third intermediate horizon between 164.73 and 169.9 m (Section Vb according to Hoselmann 2008) and the underlying sandy-gravely beds, are assigned a Lower Pleistocene age. The Lower Pleistocene (Tegelen) is confirmed at 132 m be the gastropod *Gastrocopta moravica oligodonta* (Krolopp, 1979) (Fig. 2), and at 174 m by the previously unknown *Gastrocopta n. sp.* (Fig. 3), and at 182,5 by the mollusc *Corbicula cf fluminalis* (O. F. Müller, 1774) and the Arvicolidae *Mimomys ostramosensis* (Janossy & van der Meulen, 1975) (Fig. 8). The transition to the Pliocene contains plant remains but no molluscs, as in all of the samples looked at. The drill site was selected to penetrate the most undisturbed possible sequence of Pleistocene sediments (Hoselmann 2008).

2.4.1 Upper Middle Pleistocene

The upper part of the borehole between 39.79 and 58.55 m depth, contains an almost 20 m thick bed of the Oberer Zwischenhorizont. Typical forest-type molluscs are not present. The molluscs are mainly climate-insensitive species of wet flood plain habitats of which *Vitrea crystallina* (O. F. Müller, 1774) is the most common. This indicates that the climate was rather cool (Ložek 1964). The picture is dominated by species common to periglacial, open landscapes and sparse forest steppes. *Trochulus hispidus* (Linnaeus, 1758) ("*Trichia hispida*" in older references) as well as amber snail species *Succinella oblonga* (Draparnaud, 1801) and *Succinea putris* (Linnaeus, 1758) are frequent. This thick intermediate horizon is obviously not the same as that in Ludwigshafen.

These may be the pre-Eemian or Early Holsteinian interbeds described by Schweiss (1988) from the Gernsheim and Groß-Rohrheim area. The chronostratigraphic interpretation is based on pollen analysis which indicates the pre-sence of shallow peat bogs and sparse birch and spruce growth.

The "*crassitesta*- intermediate horizon" must therefore lie much deeper because of the much thicker deposition in the eastern part of the Upper Rhine Graben. Engesser & Münzing (1991) also subdivide the OZH into three horizons with different climatic conditions. Investigations in the Karlsruhe and Mannheim areas led to a subdivision into a lower zone of interglacial Cromerian Complex sediments, followed by a middle and upper zone both marked by glacial environments, of which the upper is classified as Rissian.

2.4.2 Lower Middle Pleistocene

The species diversity in the Kieslager increases beneath the Oberer Zwischenhorizont. A mixed fauna is present at 70 m consisting of a *Fruticicola fruticum* fauna, indicating a forest steppe environment, as well as a *Succinella oblonga* fauna with a high proportion of *Pupilla muscorum* (Linnaeus, 1758), which indicates cooler steppe conditions. In addition, there is also the pea clam (*Pisidium casertanum ponderosum* Stelfox, 1918) which is adapted to cold and extreme environmental conditions.

The *fruticum* fauna which had its optimum at 89 m because it is joined by climatically more sensitive species such as *Pomatias elegans* (O. F. Müller, 1774), *Ena montana* (Draparnaud, 1801), *Discus perspectives* (Megerle von Mühlfeld, 1816), *Vertigo pygmaea* (Draparnaud, 1801) and *Monachoides incarnatus* (O. F. Müller, 1774). These species here indicate a much warmer period. This is the "*crassitesta* intermediate horizon" in the Maudach and Lindenhof boreholes. Seven metres deeper at 97 m, cooler steppe conditions dominate again and the molluscs are largely dominated by *Pupilla muscorum*, *Succinella oblonga elongata* Sandberger and *Trochulus hispidus* (cf. Chap. 2.3). There are also frequent *Clausilia* remains. Particularly interesting are five well preserved apertures of *Neostyriaca corynodes.* This is the subspecies *ornatula* (Andreae 1884), which has been identified in the Lower Pleistocene to the Lower Middle Pleistocene in Central Europe (Nordsieck 2007). It is characteristic of the "Upper Biharium" (Late Biharium, cf. Koenigswald 2007) in Cromer. Associated species are *Clausilia cruciata* (Studer, 1820) and *Clausilia dubia* (Draparnaud, 1805). This species seems to be indifferent to the climate, analogous to its associated species (Nordsieck 2006).

2.4.3 The Lower Pleistocene

The Kieslager is underlain between 131.23 and 133.18 m (Section VIIb after Hoselmann 2008) by another thin intermediate horizon with calcareous loam sand. A small snail belonging to the genus *Gastrocopta,* now extinct in Central Europe, clearly indicates a Lower Pleistocene assemblage from 132.5 m. The specimen is a well preserved shell of *Gastrocopta moravica oligodonta* (Krolopp 1979) (Fig. 2). Whilst the sediment one metre higher contains a mixed fauna indicative of a cooler "*Chondrula tridens* –steppe fauna" and a cold-moist flood plain forest fauna with a high proportion of *Perforatella bidentata* (Fig. 1) typical of open, glacial conditions, this intermediate horizon contains more thermophilic species representative of a flood plain forest. Some of the freshwater molluscs and a large number of amber snails indicate the existence of stagnant to slowly flowing waters with highly vegetated banks.

A strong increase in steppe elements, particularly *Granaria frumentum* (Draparnaud, 1801), is found in an approximately 5 m thick intermediate horizon between 164.7 and 169.9 m (Section IVb after Hoselmann 2008). This is the zone in which the bi-toothed snail *Perforatella bidentata* (Gmelin, 1791) which lives in flood plains reaches its greatest concentration in the Viernheim research boreholes. Two fragments may come from the larger, related species *Perforatella dibothrion* (M. v. Kimakowicz, 1884). There are also remains of *Clausilia rugosa antiquitatis* (Nordsieck, 1990) and the forest species *Azeca goodalli* (A. Férussac, 1821). Kieslager with sandy horizons and silty clays form alternating interbeds below the intermediate horizon and are part of an alternating sequence of interglacial and glacial sediments found in the section down to 182 m. This is indicated by the different mollusc fauna which suggest a landscape consisting of sparsely wooded forests and open steppe (*fruticum* and *tridens* fauna).

More evidence for the Lower Pleistocene is found at 174 m in the form of a previously unknown species of the genus *Gastrocopta* (Wollaston, 1878). The special feature of the shell is the absent basal tooth in the aperture armature. This *Gastrocopta* may be linked to that described from the Lower Pleistocene by Kielniki (Poland). This is found in a fauna with *G. serotina* (Ložek, 1964) and is related by Stworzewicz (1981) to *Gastrocopta theeli* (Westerlund, 1877). However, the basal tooth found in *Gastrocopta theeli* is absent in the figure on Table 1 (Fig. 3). The first classification as *Gastrocopta turgida quadriplicata* Sandberger was not confirmed.

An approx. 2.60 m thick gravel-bearing fluviatile sand horizon starts at 182.5 m and is followed by an approx. 2 m thick intermediate horizon (Section IVb after Hoselmann 2008). The shell remains of molluscs in the gravel-bearing horizon are strongly corroded or polished which indicates strong transport of the sand and gravel. Half of the aquatic species found consist of small molluscs such as *Sphaerium corneum* (Linnaeus, 1758), *Musculium lacustre* (O. F. Müller, 1774) and *Corbicula fluminalis* (O. F. Müller, 1774).

The sample contained two shell remains of *C. fluminalis* with the characteristic hinge. *C. fluminalis* is only known in Germany from the Holsteinian and the Tegelen. This species appears in Europe in the Late Pliocene and has its widest distribution during the Tegelen (Meijer & Preece 2000).

Another important stratigraphic discovery is the well preserved molar (M2) of a water vole (Arvicolidae), found in the sample from a depth of 182.4 m. Dr. Lutz Christian Maul (Senckenberg Institute, Weimar) identified the specimen as a molar from *Mimomys ostramosensis* (JANOSSY & VAN DER MEULEN, 1975) (Fig. 9). Although not unusual, it is fairly rare to find identifiable remains of small rodent fossils in material collected from boreholes (WEDEL 1999). The distribution of Arvicolidae species is now very well known in Europe and tied to chronostratigraphic tables. Analogous to *Corbicula fluminalis,* this water vole lived in the "Lower Biharium" (*Mimomys pusillus – Mimomys savini*- zone, KOENIGSWALD 2007), and the "Villanyium" approx. 1.6 to 2.0 million years ago. This species has previously only been found at a few locations in Europe (MAUL 2002). This is only the second identification of this species in the Upper Rhine area in addition to Neuleinigen near Grünstadt (MALEC & TOBIEN 1976). HEIDTKE (1979) dated the Neuleinigen fauna, also on the basis of large mammal fossils, as Lower Pleistocene with a dry-warm to subtropical climate. The fossils were found in the material filling a fissure (Neuleinigen 11) in a limestone quarry. HEIDTKE climatically compared Neuleinigen with the fauna from Hohensülzen (STORCH et al. 1973) reporting that the older Hohensülzen fauna represented the moist-warm river valleys, and Neuleinigen the topographically higher dry steppe.

The smaller two-metre-thick intermediate horizon in the Viernheim research borehole is underlain by an approx. 3.80 m thick, carbonate-rich, gravely sand bed which gradually grades into the sandy-silty series of the Lowest Quaternary. This sequence of interbedded rocks extends down to 224 m where they are underlain by limnic-fluviatile Pliocene sediments (HOSELMANN 2008). This sandy-silty suite again documents fluctuating climatic conditions where the climate optimum at 196.5 m is indicated by fewer forest-living molluscs (*Fruticicola fruticum, Vitrinobrachium breve, Discus rotundatus*). Forest species are absent at 194 m. Open landscape species such as *Pupilla muscorum* are dominant. These molluscs may indicate the earliest glacial period of the Pre-Tegelen in the Lower Quaternary. There is now a significant general decline downwards in the number of species and individuals. The last mollusc remains are found at 223 m comprising only three freshwater species and one terrestrial species. In contrast, the samples now contain large quantities of plant remains.

3 Comments on biostratigraphically important species

Perforatella bidentata (GMELIN, 1791) and *Perforatella dibothrion* (*M. v. KIMAKOWICZ, 1884*)

P. bidentata (fig. 1) is often found in the Pleistocene sands and fine-clastic intermediate horizons of the Upper Rhine Graben. It is particularly common in the Lower Pleistocene deposits in the Viernheim research borehole. Occurrence are known into the Late Eemian (MÜNZING 1999). The species can be easily identified on the basis of the two teeth (basal and palatal) in the lower aperture area. This is a pure flood plain snail (alder marsh) which requires a wet habitat. It is found in both interglacial as well as glacial contexts. It still lives in eastern Central Europe (Thuringia, Bavaria, Saxony, Austria, Czech Republic, Slovakia, Poland and Hungary) and at scattered localities in south-eastern Scandinavia. The species was found far to the west in the Pleistocene. This is confirmed by specimens collected near Paris by GEISSERT (pers. comm.)

The related species *Perforatella dibothrion* is a type fossil for the interglacial habitats of the Rhine valley in the Lower Pleistocene and Lower Middle Pleistocene. GEISSERT (1970) found a complete example in the Mosbacher Sande 2 and reports several discoveries in gravel pits in the Upper Rhine (GEISSERT 1969). Two fragments were found in the sample from 167.35 – 167.45 m in the Viernheim borehole, which may belong to this species. RÄHLE (2005) also mentions *Perforatella* remains which he assigns to this species, from the Oberer Zwischenhorizont in borehole P18 Mannheim-Lindenhof. The main differences to *P. bidentata* are a much higher aperture and two stronger teeth, although the space between the two teeth is narrower than in *P. bidentata*. The shell has clear ribs, and the first whorls have a surface structure with small scales. This species is only found alive today in eastern Slovakia and in the Carpathians where it lives in the sub-mountainous zone in moderately wet deciduous forests (Kerney et al. 1979). Its distribution in the Late Pleistocene in Europe was continental-Atlantic, i.e. much broader than today.

Gastrocopta (Vertigopsis) moravica oligodonta (*Krolopp 1979) (Fig. 2)*

This is the first confirmation of this species in the Upper Rhine Graben, and comes from the Viernheim research borehole. The shell is less conical than the nominate form *G. moravica* (Petrbok, 1959). The intraparietal tooth of the aperture is reduced to a thickening at one point. Krolopp (1979) found it together with *Gastrocopta serotina* (Ložek, 1964) in Hungary near Szabádhidvég (comm. Feyér). Both these species had previously only been identified in the Lower Pleistocene (Upper Villanyum – Lower Biharium). These two species are therefore very chronostratigraphically significant as type fossils for the Late Tegelen (Krolopp 1986). The *Gastrocopta* genus is extinct in Europe. The youngest representative of the genus in the Pleistocene is the species *Gastrocopta theeli* (Westerlund, 1877).

Rähle (1995) found *G. moravica oligodonta* in argillaceous high flood deposits in Uhlenberg (Iller-Lech Plate, Bavarian Swabia). The Uhlenberg fauna contains molluscs which were also encountered in Viernheim in samples from 131 m and 182 m, and are characteristic species for the Lower Pleistocene. In addition to *G. m. oligodonta*, another interesting find was a fragment possibly belonging to *Cochlostoma salomoni* (Geyer, 1914). Geissert (1983) mentions this species from Rhine sediments at Gambsheim and La Wanzenau, which are classified as Tegelen. Further interesting species are *Clausilia rugosa antiquitatis, Azeca godalli* and *Ena montana*. All of these species are assigned to the interglacial fauna elements, whereby the two *Gastrocopta* species were already part of Pliocene faunas and are unknown beyond the Lower Pleistocene.

Chondrula tridens (O. F. Müller, 1774) and *Granaria frumentum* (Draparnaud, 1801) are possible indicators of steppe landscapes at the edge of the flood plain forests. Both species have recently become much rarer in Europe because their habitats are virtually no longer existent.

Gastrocopta (Vertigopsis) sp. (Fig. 3)

The small conical shell is 1.9 mm high and 1.0 mm wide. The five arched whorls increase uniformly in size up to the penultimate whorl – the last whorl becomes smaller towards the aperture. The apertural border with the lip is well formed and slightly folded over towards the spindle. The shell is shiny, slightly stripy and has a weakly developed palatine torus. It has three strong teeth, one columellar, one palatal and one parietal, although the adjacent palatine wall of the specimen is damaged and partially missing. The teeth are almost the same distance apart and their tips almost point towards one another. A characteristic feature is the complete absence of a basal tooth. This form has not previously been identified in the Pleistocene.

4 Conclusions

Fossil molluscs were investigated from three research boreholes drilled in the Heidelberg Basin. Special attention was given to the Oberer Zwischenhorizont (OZH) because, particularly at the western margin of the Upper Rhine Graben, it stands for the Middle Pleistocene interglacials which are assigned to the Cromerian Complex. Whilst the OZH is relatively thick at Ludwigshafen and already encountered at a depth of around 21 m, the similar or slightly thinner horizon is first encountered in Viernheim at a depth of around 39 m. A lower horizon in the Viernheim borehole lying at around 50 m depth contains a mollusc fauna probably derived from the earlier Holsteinian period. A much thicker intermediate horizon is found as the deepest horizon between 195 and 223 m at the boundary to the Tertiary. It is divided up by several small

Kieslager (gravel horizons). Evidence of Lower Pleistocene mollusc assemblages have already been found above this horizon from 132 m. The findings support the assumption proposed by ENGESSER & MÜNZING (1991), that the Oberer Zwischenhorizont covers two to three climatically different epochs, whereby the deepest horizon in the Rhine Graben can be assigned to the Lower Pleistocene on the basis of its fossils, whilst the upper horizons have Pre-Eemian or Holsteinian character.

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Table 1: Research borehole Ludwigshafen Parkinsel P34.

Tab. 1: Forschungsbohrung Ludwigshafen Parkinsel P34.

Classification	qp(a)				tpl			
Parkinsel P34	OZH	OZH	UZH	UZH	Reuver?			
Art:	20.50-21.00	36.8-37.5	147.8-148.0	160.3-160.4	176.0-176.5	207.8-208	232.2-232.4	290.7-290.8
Aegopinella sp.	1							
Clausiliidae indet.	1							
Trochulus sp.	1							
Vertigo sp.	3							
Vertigo substriata	3							
Oxyloma elegans	1							
Succinea putris	1							
Pisidium amnicum	1							
Musculium lacustre	2							
Valvata cristata	125							
Planorbis planorbis	5							
Lymnaeidae indet.	200							
Stagnicola aff. palustris	2							
Valvata macrostoma	1							
Acroloxus lacustris	2							
Gyraulus crista	30							
Hippeutis complanatus	3							
Planorbarius corneus	6							
Sphaeriidae indet.	90	2						
Galba truncatula	6							
Bithynia tentaculata (Opercula)	85					1		
Bithynia tentaculata	4							
Valvata piscinalis	6							
Viviparus sp. (Opercula)	1							
Pisidium pulchellum	10							
undetermined fragments of molluscs	2			1				1
Number:	592							
Piece of plants	x	x	x	x	x	x	x	
Charophyts	x							
Small mammals	x							

OZH = Oberer Zwischenhorizont; UZH = Unterer Zwischenhorizont; qp(a) = Older Pleistocene; tpl = Pliocene

Table 2: Research borehole of Ludwigshafen Parkinsel P35/P35a (first part).

Tab. 2: Forschungsbohrung Ludwigshafen Parkinsel P35/35a (erster Teil).

Classification:	qp								tpl		
Parkinsel P35 / P35a	OZH					OSF		USF	(P35a)		
Species:	21.90	26.33-26.37	27.2-27.24	27.8-28.0	30.26-30.3	50.0-50.3	88.70	178.00	236.10	276.20	287.5-287.9
Clausiliidae indet.	6							1	n. F.	n. F.	n. F.
Vitrinobrachium breve	1										
Aegopinella sp.				1							
Aegopinella nitens				1							
Monachoides incarnatus				1							
Arianta arbustorum	4					1					
Vitrea crystallina	1							2			
Perforatella bidentata	8			1							
Vallonia excentrica	3										
Vallonia pulchella	1										
Vertigo pygmaea	2					2					
Pupilla muscorum	2							1			
Vertigo sp.	2					3					
Trochulus sp.	2	1				4		1			
Cochlicopa lubrica Komplex	3										
Punctum pygmaeum	4										
Deroceras laeve	1										
Vertigo angustior	3										
Succinella oblonga						4		1			
Vertigo substriata	1										
Carychium tridentatum	4										
Carychium minimum	2										
Oxyloma elegans	3										
Succinea sp.	2										
Vallonia enniensis	1										
Succinea putris								1			
Unioniidae indet.								4			
Pisidium amnicum				2				5			
Borysthenia naticina						2					

Table 2: Research borehole of Ludwigshafen Parkinsel P35/P35a (second part).

Tab. 2: Forschungsbohrung Ludwigshafen Parkinsel P35/35a (zweiter Teil).

Classification:	qp								tpl		
Parkinsel P35 / P35a	OZH					OSF		USF	(P35a)		
Species:	21.90	26.33-26.37	27.2-27.24	27.8-28.0	30.26-30.3	50.0-50.3	88.70	178.00	236.10	276.20	287.5-287.9
Musculium lacustre						8					
Segmentina nitida	1										
Valvata cristata	3					8					
Planorbis planorbis	7					9		1			
Lymnaeidae indet.	4					5		4			
Anisus spirorbis	4					5					
Gyraulus albus			1					1			
Gyraulus crista	3					17					
Lymnaea stagnalis						1					
Pisidium sp.					1						
Planorbarius corneus	2					3		1			
Sphaeriidae indet.	2					4					
Galba truncatula	4					5					
Bithynia tentaculata (Opercula)	4				12	16					
Bithynia tentaculata						2					
Valvata piscinalis						1					
Bathyomphalus contortus						2					
Number:	90	1	1	6	13	102	0	23	0	0	0
Piece of plants	x	x	x	x	x		x		x	x	x
Ostracods	x					x					
Piece of fishs									x		x
Small mammals			x				x				
Piece of insects		x									

n. F. = no Fauna; OZH = Oberer Zwischenhorizont; OSF= Obere sandige Folge; USF= Untere sandig-schluffige Folge
pl = Pleistocene; tpl = Pliocene (only borehole P35a)

Table 3: Borehole Ludwigshafen-Maudach A-36.

Tab. 3: Bohrung Ludwigshafen-Maudach A-36.

Classification:	Middle-Pleistocene			
Lu-Maudach A 36	OZH			
Art:	23.10 - 23.40	26.40- 26.80	27.50- 28.00	**number:**
Clausiliidae indet.	7	1	7	15
Clausilia bidentata	2	1	2	5
Discus ratus rude			1	1
Vitrinobrachium breve			5	5
Aegopinella la nitidu			1	1
Ena na monta			3	3
Helicodonta obvoluta		2	2	4
Macrogastra lineolata		2	1	3
Monachoides incarnatus		1	1	2
Azeca lli gooda			2	2
Arianta arbustorum	2	1		3
Vitrea crystallina	3	3	4	10
Discus rotundatus	1	2		3
Limax inereoniger c		1		1
Cepaea hortensis	2	1	1	4
Clausilia pumila	3	5	6	14
Perforatella bidentata	7	8	29	44
Chondrula ns tride			3	3
Pupilla terri s			1	1
Pupilla nsegyrata de		2		2
Vallonia excentrica		3	1	4
Vallonia pulchella	6	2	9	17
Vallonia declivis			1	1
Vallonia costata	5		5	10
Pupilla muscorum		3	17	20
Columella olumella c		1		1
Vallonia tenuilabris			1	1
Cochlicopa ella lubric			1	1
Trochulus sp.	2	1	1	4
Vertigo sp.	8	3		11
Clausilia rugosa antiquitatis			2	2
Cochlicopa lubrica Komplex	2	3	4	9
Euconullus fulvus	1		1	2
Nesovitrea hammonis		2	11	13
Trochulus hispidus	1		3	4
Clausilia dubia		1	3	4
Helicigona lapicida	2	1	1	4
Columella dentula e			3	3
Deroceras leave	2		1	3

Vertigo substriata	3			3
Succinella oblonga	21	26	290	337
Succinella elongata		1	3	4
Carychium um minim	1			1
Oxyloma legans e			3	3
Vallonia enniensis	1	1	3	5
Vertigo genesii	1	6	44	51
Vertigo geyeri			1	1
Pseudotrichia ginosa rubi	1			1
Zonitoides nitidus			2	2
Ancylus fluviatilis	3	2	3	8
Borysthenia naticina		3	1	4
Valvata cristata			8	8
Valvata macrostoma		1	10	11
Valvata piscinalis	9	2	21	32
Bithynia sp.	26	100		126
Parafossarulus crassitesta	6	5	20	31
Bithynia tentaculata	1	1	4	6
Bithynia leachii		3	2	5
Planorbis planorbis	5	4	9	18
Planorbarius corneus	2	1	2	5
Planorbis arinatus c	1			1
Anisus leucostoma	1	3	9	13
Bathyomphalus contortus	1		2	3
Hippeutis complanatus			3	3
Segmentina nitida			2	2
Gyraulus albus	1		4	5
Gyraulus laevis		1	1	2
Lymnaeidae indet.	2		2	4
Stagnicola agg. palustris			2	2
Radix balthica		1	12	13
Radix balthica aff. ampla			5	5
Lymnaea stagnalis			4	4
Galba truncatula	6	8	5	19
Sphaeriidae t. inde		1		1
Sphaerium orneum c	2			2
Pisidium sp.		1		1
Pisidium amnicum	4	4	30	38
Pisidium upinum s			4	4
Pisidium obtusale lapponicum			9	9
Pisidium ssierianummoite		2		2
gesamt:	154	227	654	1035
Charophyts-Oogonie	x	x	x	
Piece of fishs	x	x	x	
Small mammals	x	x	x	

OZH = Oberer Zwischenhorizont

Table 4: Research borehole of Viernheim (first part).

Tab. 4: Forschungsbohrung Viernheim (erster Teil).

Classification:	Pleistocene																												Tertiär	
Viernheim FB 1	qp (j)					qp (m)											qp (a)												tpl	
Species:	12.00-13.00	18.00-18.50	35.85-36.00	46.43-46.56	49.60-49.70	50.10-50.30	51.70-51.80	53.90-54.00	59.70-59.80	66.30-66.45	70.00-70.30	89.40-89.70	96.90-97.00	104.10-104.20	108.00-108.20	115.90-116.00	131.25-131.45	132.60-132.70	155.20-155.40	164.00-164.20	167.35-167.45	174.30-174.40	182.30-182.50	194.50-194.60	196.45-196.60	204.75-204.80	214.00-214.20	223.00-223.15	228.75-228.85	239.08-310.70
Clausiliidae indet.	3	4	3		5			1		6	9	4	**20**	**10**			1	2		7	**14**	1	7		7		3			k.F.
Clausilia cruciata													2																	
Vitrinobrachium breve					1						3														2					
Aegopinella sp.												3		1			1			2	2					1				
Ena montana												2		1				1		2										
Helicodonta obvoluta														1																
Monachoides incarnatus					1							1	1	1				2		1	1				4		1			
Perforatella dibothrion																					2									
Aegopis sp.																							1							
Azeca goodalli																				1			4							
Discus perspectivus												1																		
Arianta arbustorum		4			**9**							1		2					5	7	4			1	5	1		1		
Fruticicola fruticum			1	1	5		1	1	1	2	**12**		5	1			3			1	4									
Vitrea crystallina	1	1	1		7	3		1		2	**20**	4	1	5						1				2	1	1				
Discus rotundatus																									4					
Pomatias elegans					1							1		4																
Neostyriaca corynodes ornatula											1		5																	
Monachoides cf. vicinus																								1						
Perforatella bidentata			1		7			1		1	1	4	2	7			**16**	8		7	**20**	5	2	5	**10**					
Cepaea sp.																					2									
Chondrula tridens																	3			1										

Table 4: Research borehole of Viernheim (second part).

Tab. 4: Forschungsbohrung Viernheim (zweiter Teil).

Classification:	Pleistocene																												Tertiär	
Viernheim FB 1	qp (j)					qp (m)											qp (a)												tpl	
Species:	12.00-13.00	18.00-18.50	35.85-36.00	46.43-46.56	49.60-49.70	50.10-50.30	51.70-51.80	53.90-54.00	59.70-59.80	66.30-66.45	70.00-70.30	89.40-89.70	96.90-97.00	104.10-104.20	108.00-108.20	115,90-116,00	131.25-131.45	132.60-132.70	155.20-155.40	164.00-164.20	167.35-167.45	174.30-174.40	182.30-182.50	194.50-194.60	196.45-196.60	204,75-204,80	214.00-214.20	223.00-223.15	228.75-228.85	239.08-310.70
Granaria frumentum												1					1			**11**	**30**		2				3			
Vallonia excentrica																								2						
Vallonia pulchella			1									3	2							3										
Vallonia costata					3									1																
Pupilla muscorum	3	5	3		5			1		3	**21**	7	**29**	7			1			2	6	5		**12**						
Columella columella										1																				
Vallonia tenuilabris										1	1																			
Cochlostoma sp. (cf. salomoni)																						1								
Cochlicopa lubricella		1																												
Gastrocopta sp.																						1								
Gastrocopta moravica oligodonta																		1												
Vertigo sp.											2		3								5	1								
Trichia sp.			3	1	5		1	7	2	**12**	**13**	8	**44**	**10**	1		9	1	4	2	4	2		5	6					
Cochlicopa lubrica Komplex		2			1			1		2	1		3	1	2		1	2		4	1			1	2					
Clausilia rugosa antiquitatis																				2	1									
Nesovitrea hammonis													1																	
Triochulus hispidus	3	7			2					4	**12**		**26**					1				1								
Limacidae / Agriolimacidae Komplex		1			4			2						1											1		1			
Oxychilus sp.								2																						
Oxychilus cellarius													2																	

Clausilia rugosa parvula													1																	
Clausilia dubia	1												2																	
Helicigona lapicida					1				1								1		1	2	4		1		3		2			
Succinea sp.							3	1												1	**11**		5							
Columella edentula											5		1																	
Vallonia declivis													1																	
Succinella oblonga	4	9	4						2	**17**	**25**	2	4	6			1			2		1								
Succinella oblonga elongata													**16**																	
Carychium minimum																					1									
Oxyloma elegans											6		4									2								
Vallonia enniensis					2															1										
Succinea putris					**10**	**25**					3		2					4		1						1				
Unioniidae indet.																			1											
Lithoglyphus naticoides							1																							
Pisidium supinum																				1										
Theodoxus fluviatilis														1																
Ancylus fluviatilis														2																
Borysthenia naticina																				1										
Corbicula fluminalis																							2							
Musculium lacustre																	2									1				
Valvata cristata																					1		1					3		
Planorbis planorbis	1	1	1		1	**14**	2	1	1	1	**11**	1	3	1			2	2		3	2		1			5				
Lymnnaeidae Komplex	1	1			2	5				1	5		5	2										1		7				
Stagnicola agg. palustris	1										3			2			1	1		1										
Pisidium obtusale																									8					
Pisidium casertanum ponderosum											1	1		1																
Anisus spiorbis														1									1		1					
Anisus leucostoma			1			6					2	1					1	1			1									
Aplexa hypnorum					1	3																								
Valvata macrostoma	2					9	1	2			2																			

Classification:	Pleistocene																												Tertiär	
Viernheim FB 1	qp (j)					qp (m)											qp (a)												tpl	
Species:	12.00-13.00	18.00-18.50	35.85-36.00	46.43-46.56	49.60-49.70	50.10-50.30	51.70-51.80	53.90-54.00	59.70-59.80	66.30-66.45	70.00-70.30	89.40-89.70	96.90-97.00	104.10-104.20	108.00-108.20	115.90-116.00	131.25-131.45	132.60-132.70	155.20-155.40	164.00-164.20	167.35-167.45	174.30-174.40	182.30-182.50	194.50-194.60	196.45-196.60	204.75-204.80	214,00-214,20	223.00-223.15	228.75-228.85	239.08-310.70
Anisus vorticulus												1																		
Gyraulus sp.																												2		
Gyraulus albus									1	1					1			1												
Gyraulus crista						8														1			1							
Hippeutis complanatus								1																						
Physa fontinalis						5																								
Pisidium sp.								1			1	2	2	2														2		
Planorbarius corneus											2	1		2			2	5	2	7	3									
Planorbis carinatus																						1								
Radix labiata																	1													
Sphaeriidae indet.		1	1								1			1	2					1										
Sphaerium corneum					5	4																	2							
Galba truncatula					6	**25**	9	4	2	2	**11**	1	6	**11**			**10**	4	1	1	**16**		2							
Bithynia sp.								1	9					2																
Bithynia tentaculata							7		2		6			3	1		**11**		2	4			3							
Pisidium subtruncatum		1												1																
Valvata sp.									1				3												1					
Valvata piscinalis alpestris														3																
Valvata piscinalis					2			2																						
undetermined fragments of molluscs																8														
number	20	38	20	2	86	**107**	25	30	22	56	**180**	50	**196**	94	7	8	68	37	16	81	**135**	22	35	30	55	17	10	8		
small mammals				x										x			x	x					**X***					x		
charophyts																			x	x										
Piece of plants			x	x			x	x		x		x			x				x	x			x					x	x	

X* = *Mimomys ostramosensis* n.F.*= no fauna

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Evidence for a Waalian thermomer pollen record from the research borehole Heidelberg UniNord, Upper Rhine Graben, Baden-Württemberg

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Abstract: A pollen record from the borehole Heidelberg UniNord, in the northern Upper Rhine Graben shows evidence for one of the rare Waalian thermomers. The record may not comprise the complete thermomer it certainly reflects a sort of succession, initiated by sequences with high values of pine and spruce, followed by a dominance of pine, hemlock-spruce and spruce and finished by a dominance of hemlock-spruce, oak and hornbeam becomes visible. Pollen percentage values for *Tsuga* reach 20 % indicating that this taxon is an important forest element. There is a continuous presence of *Carya, Pterocarya, Eucommia*, *Celtis* and *Ostrya*-type. Neighbouring pollen records reveal similar patterns. The pollen diagram is closely related with the Waalian profiles Leerdam and Eindhoven from the Netherlands.

[Nachweis der Waal-Warmzeit anhand pollenanalytischer Untersuchungen an der Forschungsbohrung Heidelberg UniNord, Oberrheingraben, Baden-Württemberg]

Kurzfassung: Eine Pollensukzession aus der Bohrung Heidelberg UniNord im Oberrheingraben kann mit der bisher selten nachgewiesenen Waal-Warmzeit verknüpft werden. Das wohl nicht vollständig erfasste Thermomer reflektiert eine angedeutete Sukzession, die von einer basalen Fichten-Kiefernzeit über einen Abschnitt mit Kiefer, Hemlocktanne und Fichte, hin zu einer abschließenden Waldzeit verläuft, in der Hemlocktanne (*Tsuga*), Eiche und Hainbuche dominieren. *Tsuga* erreicht im Gesamtdiagramm Werte bis zu 20 % und repräsentiert ein wichtiges Waldelement. Ständig vorhanden sind in geringen Anteilen ferner *Carya*, *Pterocarya*, *Celtis, Eucommia* und *Ostrya*-Typ. In Nachbarbohrungen deutet sich dasselbe Muster an. Das Pollendiagramm wird korreliert mit den Waal-Profilen aus Leerdam und Eindhoven (Niederlande).

Keywords: Upper Rhine Graben, pollen analysis, Waalian thermomer, biostratigraphy

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1 Introduction

In order to develop a better understanding of the Pleistocene geological processes associated with the evolution of the Upper Rhine Graben (URG), a scientific core drilling has been brought down at the campus of Heidelberg University. In this location, one of the thickest successions of continental Quaternary deposits has been expected according to various pre-site surveys (Buness, Gabriel & Ellwanger 2008). For technical reasons, a first borehole (Heidelberg UniNord1) has been cored down to 190 m in 2006, followed by a second borehole (UniNord2) down to 500 m in 2008. For a first summary of geological results, cf. Ellwanger et al. (2008); for an outline of the Heidelberg project cf. Gabriel et al. (2008).

In this paper, only results from the first borehole (0 – 190 m; UniNord1) have been evaluated. According to Ellwanger et al. (2008), only about one third of the succession consists of fine-grained i.e. silt-dominated deposits. Out of these, only three intervals, altogether amounting to less than five meters of sediment core, turned out to be suitable for a detailed pollen analysis (57 – 58 m; 81 – 87 m and 180 – 181.70 m). The remaining 65 m of silt-dominated sediments were poor in pollen-content. This may be due to oxidation and differential preservation of the pollen, e.g. concentration of thick-walled grains such as conifers and *Tilia*, but also of poor core quality.

The biostratigraphic review maybe summarized as follows:

(1) At 57 – 58 m and 82 – 85 m depth a pine-spruce forest indicating cool climate;
(2) At 81 – 82 m and at 87 m depth a middle Pleistocene pollen spectrum without *Fagus* indicates an interglacial environment is indicated;
(3) At 180 – 181.70 m depth some very pollen rich samples were found in peaty sediments with more or less silt. The higher pollen percentage values of the genus *Tsuga* (Hemlock spruce) indicates a temperate "interglacial" resembling an early Pleistocene age.

This study is focused on the interval (3).

2 Methods

Peaty samples were taken at 10 cm intervals. In total, 17 pollen samples were analysed. Samples were subjected to HF (70 %) treatment followed by ultrasonic sieving (mesh size 6 x 8 µm) then acetolysis. With the exception of the two oldest samples, arboreal pollen counts of at least 500 were attained. The basis for representation on the pollen diagram was the total pollen sum (all pollen types excluding aquatics and ferns). The pollen diagram (Fig. 2) was prepared using the plotting program Tilia (Grimm 1991). Non-arboreal taxa that were only encountered in few samples and in low numbers are not shown on the diagram. Values below 1 % are also represented (symbol "•").

3 Results

The pollen diagram (Fig. 1) is divided into three local pollen zones (A, B and C):

- A: 181.70 – 181.15 m: *Pinus – Picea* zone (with ferns)
- B: 181.15 – 180.55 m: *Pinus – Tsuga – Picea* zone
- C: 180.55 – 180.00 m: *Tsuga – Quercus – Carpinus* zone (with *Alnus* and *Betula*)

The local pollen assemblage zone A is characterized by a dominance of *Pinus* and *Picea,* ferns are of great importance. The arboreal taxa such as *Tsuga, Ulmus*, *Corylus*, *Carpinus* and *Eucommia* are present with rates up to 2 %, *Quercus* ranges between 2-5 %.

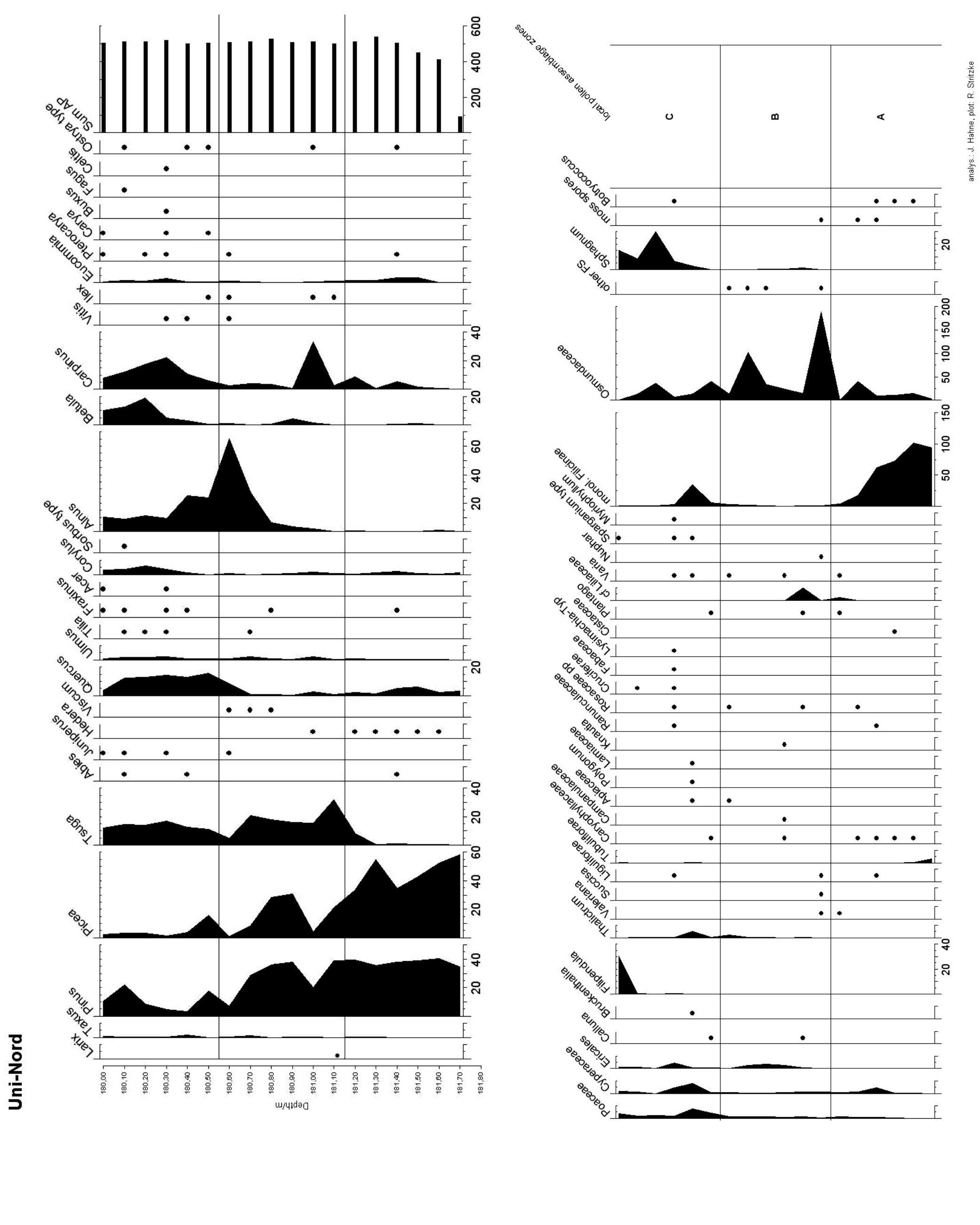
In zone B *Tsuga* (and *Alnus*) is increasing and represents an important forest element.

Zone C reflects a dominance of *Tsuga* (10-15 %), *Quercus* (10-15 %) and *Carpinus* (10-25 %) (together with *Alnus* and *Betula*). *Pinus* and *Picea* are of less importance. Typical elements of Older- and Middle Pleistocene such as *Pterocarya*, *Eucommia*, *Carya*, *Celtis* and *Ostrya*-type are continuously present in low rates. *Fagus* is limited to sample 180,10 m where two pollen grains are recorded.

Altogether, the succession is clearly dominated by arboreal taxa representing a thermomer stage i.e. warm climate. Non arboreal pollen

Fig. 1: Pollen diagram of the borehole Heidelberg UniNord, interval 180 – 181.70 m. It represents a Waalian pollen assemblage. – Values below 1 % ~ "•".

Abb.1: Pollendiagramm der Bohrung Heidelberg UniNord, Intervall 180 – 181,70 m, interpretiert als Waal-zeitliche Pollen-Vergesellschaftung. – Werte unter 1 % ~ „•".



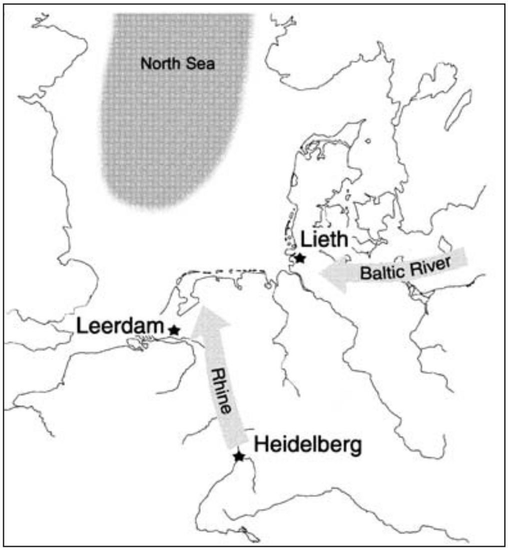


Fig. 2: Geographic position of Waalian sequences in middle Europe, Leerdam, Lieth, and Heidelberg. Present topography and palaeogeographical setting (GIBBARD 1988). Palaeo-shoreline uncertain, varying according to high and low sea level.

Abb. 2: Geographische Lage der Waal-Vorkommen in Mitteleuropa, Leerdam, Lieth und Heidelberg. Heutige Geographie und Waal-zeitliche Paläogeographie (GIBBARD 1988). Die Paläo-Küstenlinie ist unsicher, sie schwankt je nach Höhe des Meeresspiegels.

types are of less importance and mostly below 10 %, with the exception of two samples with *Filipendula* (up to 30 %!) and an unknown, very small *Liliaceae*-type. Both elements represent the influence of local swampy vegetation.

4 Discussion

According to the implied succession of the significant arboreal taxa, the pollen diagram (Fig. 1) has been divided in three pollen assemblage zones. There are, however, no taxa, which are immigrating in the course of the sequence. All are present right from the beginning.

Complete sequences of the immigration of tree species during an interglacial cycle (e.g. shrubs – birch - pine - broad leaf trees – climax zone – conifers) is well known from the Holocene, from the Eemian, and from middle Pleistocene thermomers (Holsteinian, Cromerian). These characteristics are also reported from Bavelian sequences (ZAGWIJN & DE JONG 1984). However, as indicated above, this type of succession is not recorded in the Waalian thermomer, the older Pleistocene (Tiglian thermomers) and the Reuverian.

The decrease of arboreal taxa during the Pleistocene is known from various studies. *Pterocarya* is ultimately recorded at the end of the Holsteinian (e.g. BEAULIEU & MONJUVENT 1985).

Eucommia and *Celtis* barely occupy interglacial I and II of the Cromerian-Complex, e.g. HOMANN & LEPPER (1994), HAHNE (1996a,b). VAN DER HAMMEN et al. (1971) record *Carya* and *Ostrya*-type restricted to the Older Pleistocene thermomers Waalian and Tiglian. ZAGWIJN & DE JONG (1984) report from the cores from Bavel, Netherlands, i.e. the type region of the Bavelian stage, also *Carya, Ostrya*-type and *Tsuga*.

Tsuga was the first taxon recognised as an element of the Older Pleistocene (e.g. by VAN DER HAMMEN et al., 1971). According to ZAGWIJN (1957, 1960) and HAHNE (1996a,b), this taxon is present in low levels in the Reuverian and in the Pretiglian as well as in the Tiglian A, B and C. KNIPPING (2004) recorded single pollen grains in sediments of Bavelian age, whereas ZAGWIJN & DE JONG (1984) report values up to 30 % in a profile in Bavel revealing also a distinct succession of the tree species. Quite recently, KNIPPING (2008) even stated a single pollen grain of *Tsuga* in a thermomer, which she assumed to belong to the Cromerian Complex.

On the other hand, Pliocene elements such as *Liquidamdar*, *Nyssa, Sciadopitys, Taxodium*- and *Sequoia*-habitus are not present in the pollen diagram (Fig. 1). All those are frequent in the Reuverian and, with the exception of *Sciadopitys*, very sparsely during Tiglian (ZAGWIJN 1960, 1963, 1989). Some very first results of the lower parts of the Heidelberg UniNord borehole confirm this trend (ELLWANGER et al. 2008, Fig. 3).

5 Conclusions

The pollen diagram (Fig. 1) reflects a thermomer revealing a closed forest vegetation in which pine, spruce, Hemlock-spruce, oak, hornbeam and elder were dominant. Records of Older Pleistocene elements (*Pterocarya, Eucommia, Celtis, Carya, and Ostrya*-type) are continuously present but only in low numbers. A successive immigration is not visible.

All these characteristics exclude an assignment of this thermomer to young or middle Pleistocene stages. A correlation with the Reuverian is also not possible due to the missing of Pliocene elements. For the Tiglian the presence of *Sciadopitys*, *Nyssa*, *Liquidambar*, and *Pinus haploxylon*-Habitus is compulsive. Therefore, only the Waalian and the Bavelian stages are to be taken on closer consideration.

After Zagwijn & De Jong (1984), the Bavelian fills an intermediate position between Older- and Middle Pleistocene. With respect to partly high values of *Tsuga*, the presence of *Ostrya*-type, *Celtis* and *Eucommia* an Older Pleistocene character is evident whereas a succession of the expansion of various trees due to differences in re-immigration emphasizes a strong resemblance with thermomers younger than Tiglian and Waalian.

The pollen diagram (Fig. 1) shows significant similarities with the Leerdam-Profile (Fig. 2) which is the type locality for Waalian (Zagwijn & De Jong 1984). The similarity is not restricted only to the spectra of the arboreal pollen types, but also in their values (with the exception of *Picea*, which in Leerdam has a smaller representation). Different with Leerdam is also the missing of indications of systematic suc-

	Pliocene	Older Pleistocene			Middle Pleistocene		Younger Pleist.	
	Reuverian	**Tiglian**	**Waalian**	**Bavelian**	**Cromerian**	**Holsteinian**	**Eemian**	**Holocene**
Sequoia-Hab.	O	x						
Taxodium-Hab	O	x						
Sciadopitys	O	O						
Liquidambar	O	x						
Nyssa	O	x						
Carya	O	x	x	x				
Ostrya-type	O	x	x	x				
Tsuga	O	O	O	O	x			
Eucommia	O	O	O	O	O			
Celtis	O	O	O	x	O			
Pterocarya	O	O	O	O	O	O		
Fagus	O	O	x	x	O	O	x	O

Fig. 3: Presence of important arboreal taxa in Middle European pollen sequences from the Reuverian (Pliocene) to the Holocene. Adapted from Lang (1994), updated according to actual investigations and with regard to new results from the Heidelberg research boreholes. – Symbols: O = frequent, x = rare.

Abb. 3: Vorkommen wichtiger Baumpollen in mitteleuropäischen Pollensequenzen vom Reuver (Pliozän) bis ins Holozän. Nach Lang (1994), fortgeschrieben aufgrund neuer Untersuchungen, insbesondere neuen Ergebnissen aus den Forschungsbohrungen Heidelberg. – Symbole: O = häufig, x = selten.

cession in immigration and culmination of the individual trees.

In Kronau, about 20 km south of Heidelberg, another borehole revealed cores of peaty sediments at depths around 85 m. Here several pollen samples reveal nearly identical Waalian pollen assemblages as in Heidelberg.

Zagwijn (1989) noted that the Waalian generally has the character of an interglacial complex consisting of an interstadial situated between two thermomers. A similar sequence is recorded by Menke (1976) for the "Tornesch thermomer" (Lieth series) situated in Schleswig-Holstein which is also assigned to the Waalian. Although it reveals a domination of Ericales (pointing toward Atlantic heaths) apart from *Tsuga* all Older Pleistocene elements are present. Running analysis on the cores of the UniNord2 borehole at Heidelberg reveal 26 m underneath the peaty Waalian sediments again typical Waalian pollen sequences which possibly could assigned to the older Waalian thermomer. The intermediate sediments are fluvial gravels, which, unfortunately, are poor of pollen so that their climatic character is still uncertain. Even a separation within either the upper or the lower thermomer by fluvial gravels, without any difference in climate, may be considered.

The question remains why there are such great similarities in the forest vegetation between the Upper Rhine Graben and the Netherlands, whereas from Lieth (Schleswig-Holstein, Fig.2) a quite different forest vegetation and maritim influenced different climatic conditions has been reported by Menke (1969, 1976). In our view, this indicates uniform climate conditions along the Rhine, and different conditions further east. Today the Rhenish Schist highlands act as a barrier between the Netherlands and the Upper Rhine Graben. In the Waalian stage, prior to their major uplift, the Rhenish Schist was an area of some low hills. In this scenario, there was an almost flat landscape from Heidelberg to the Netherlands, with uniform forest vegetation and climate conditions (Fig. 2).

However, K.-E Behre (Wilhelmshaven) has expressed another view (pers. comm.). The Netherlands situated in the lower Rhine area, were an excellent sediment and pollen catching area, including reworked pollen from further south. Their pollen records reflect the complete upper Rhine vegetation combined with the regional elements. On the other hand, the Lieth series (Menke 1976) reflects the regional vegetation of Holstein, maybe including input from the Baltic river system (Fig. 2).

The chronostratigraphic age of the Waalian amounts to 1.1 -1.3 Ma (Zagwijn 1989) or to 1.4 – 1.6 Ma (Ogg, Ogg & Gradstein 2008), both with duration of approximately 200 ka. Thus, the peaty sequence from Heidelberg (Fig. 1) with a length of 1.7 m does certainly not reflect one of the two thermomers as a whole, but only a shorter period belonging to either of them.

Considering the arboreal pollen types, the climate of the recorded sequence was probably not warmer than today. The present day distribution of the most important *Tsuga* species (*T. canadensis* and *T. diversifolia*) in North-East America and East Asia reflect mountainous climates and moist habitats.

According to De Jong (1988), many of the so-called Pliocene trees that are today restricted to North America or East Asia, actually do very well in European parks or as forest elements. Thus, the interglacial climates of the Early Pleistocene might not have been more favourable than in the middle or young Pleistocene, but the intermediate stadials were not as extreme as the glacial stages of that period.

Thus, for the identification of a Waalian thermomer in Middle Europe three conditions must be fulfilled:

1. no complete succession of the arboreal genera,
2. *Tsuga* must be an important member of the forest vegetation, and
3. there must be at least single records of so called Older Pleistocene elements such as *Eucommia* and *Pterocarya* and in very low rates also *Carya*, *Celtis* and *Ostrya*-type and possibly even *Fagus*.

Final remark: In summer 2008, a second drilling in Heidelberg ("UniNord2") finally reached its planned depth of 500 m. First scans of pollen content down to 499.94 m include continuous findings of *Fagus* and *Carya* as well as such of *Sciadopitys*, *Nyssa*, *Pinus haploxylon*, Cupressaceae, *Sequoia*- and *Taxodium*-habitus. The spectra are clearly different from the Waalian and represent most likely the Tiglian interval. By now, we also know that the thickness of the Quaternary at the UniNord location will amount to more than 500 m (well exceeding the originally assumed thickness of ~ 400 m). The Reuverian is expected well below 500 m.

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Timing of Medieval Fluvial Aggradation at Bremgarten in the Southern Upper Rhine Graben – a Test for Luminescence Dating

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Abstract: The Holocene flood plain of the River Rhine is a complex dynamic sedimentary system. A series of geochronological results for the Bremgarten section including optically stimulated luminescence (OSL) and radiocarbon dating was determined to improve the understanding of part of the Holocene evolution of the River Rhine. The applied single aliquot regenerative (SAR) protocols and the applied experimental studies to find the best luminescence behaviour leave us with confidence that OSL dating is a suitable method for dating fluvial sediments from large river systems. Insufficient bleaching of the sediments from Bremgarten prior to deposition seems to be not as dramatic as previously thought. OSL and radiocarbon dating results give evidence for a short period of major erosion and re-sedimentation of fluvial sediments from the "Tiefgestade" at the Bremgarten section between 500 and 600 years before present. This time period correlates with the beginning of the Little Ice Age at about AD 1450. Several severe floods occurred in Southern Germany between AD 1500 and 1750; all those floods correlate to the period of the Little Ice Age, including the destruction of the village of Neuenburg AD 1525.

[Die zeitliche Stellung einer mittelalterlichen fluvialen Sedimentakkumulation im südlichen Oberrheingraben am Beispiel Bremgarten – ein Test für Lumineszenz-Datierungen]

Kurzfassung: Die holozäne Überflutungsebene des Rheins ist ein komplexes sedimentäres System. Die geochronologischen Untersuchungen mittels Optisch Stimulierter Lumineszenz (OSL) und Radiokohlenstoff-Datierungsmethode verbessern das Verständnis der holozänen Entwicklung des Rheinsystems und ermöglichen quantitative Studien zu Aggradationsphasen von Flüssen. Die angewandten Single-Aliquot-Regenerierung (SAR)-Protokolle und die angewandten experimentellen Untersuchungen zur Absicherung der Messparameter lassen erkennen, dass die OSL-Datierungstechnik eine geeignete Datierungsmethode für fluviatile Sedimente aus großen Flusssystemen ist. Eine unvollständige Bleichung der fluviatilen Sedimente vor der Ablagerung scheint für die Sedimente aus Bremgarten nicht so dramatisch zu sein wie ursprünglich vermutet. OSL- und Radiokohlenstoff-Datierungsergebnisse bestätigen eine kurze Periode starker Erosion und Akkumulation im Bereich des Tiefgestades von Bremgarten zwischen 500 und 600 Jahren vor heute. Dieses Zeitfenster korreliert mit dem Beginn der Kleinen Eiszeit um ca. AD 1450. Mehrere schwere Flussüberschwemmungen geschahen in Süddeutschland zwischen AD 1500 und 1750. Diese Überschwemmungsereignisse korrelieren mit dem Zeitfenster der Kleinen Eiszeit, darunter die Zerstörung von Neuenburg im Jahre 1525.

Keywords: Upper Rhine Graben, river aggradation, OSL chronology, Little Ice Age, Quaternary

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1 Introduction

Investigating terrestrial sediment archives of the past is imperative to learning and understanding the future impact of climate and environmental changes. The Medieval climate optimum and the Little Ice Age are two historically recorded periods during which society was considerably influenced by climate and environment change. Fluvial landscapes in modern floodplains and lower terraces are particularly sensitive to climate change. Extreme weather events such as the millenium flood of the year AD 1342 had a catastrophic impact on Man and the society and indeed caused a significant alteration of landscape, such as up to 15 m deeply incised canyons and reworking of up to 8 m thick fluvial sediments in southern Germany (Bork 1989). The extent of the fluvial dynamics and the temporal succession of such events are not yet understood in either large or small rivers.

Extensive research has been carried out in the catchment area of the River Rhine on Pliocene and Pleistocene terrace formation (e.g. Boenigk & Frechen 2006; Hagedorn & Boenigk 2008, Westerhoff 2008; and references within) demonstrating the complexity of this major fluvial sediment archive. The large increase in terrigenous sediment supply during the Quaternary is a result of continuous disequilibrium between weathering, erosion, sediment transport and aggradation triggered by climatic perturbations (Hinderer 2001). Increased aggradation in the southern Upper Rhine Graben (URG) postdates the filling up of the Lake Constance (Bodensee) Basin and occurred synchronous with periods of major ice melting (Wessels 1998). During these highly dynamic periods, including the glacial overdeepening of Alpine valleys, the peri-alpine basins were deeply eroded. Late Glacial and Holocene fluvial aggradation and terrace formation are triggered by climate change and tectonic processes as well as human-induced adjustment of river systems (Schirmer et al. 2005; Bos et al. 2008; Erkens et al. 2009; Lämmermann-Barthel et al. in press). During the Little Ice Age, significant erosion and aggradation occurred along the Rhine.

Little is known about the timing of the Holocene fluvial activity of the River Rhine in the southern Upper Rhine Graben (URG). Historical data is available for major flood events during Medieval times. Numerical dating of fluvial sediments is problematical, as described in detail for the Middle and Lower Rhine area by Boenigk & Frechen (1998, 2006) and the northern Upper Rhine Graben by Erkens et al. (2009) and Frechen et al. (2006). During the past 15 years, much attention has been paid on the investigation of the timing of fluvial activity in the Rhine system. Fluvial sediments are particularly suitable for the application of optically stimulated luminescence (OSL) dating techniques (Busschers 2008; Jain et al. 2003; Wallinga 2002). In this study, OSL dating on fine-sand and radiocarbon dating on wood was carried out on Holocene material from the gravel pit at Bremgarten in the southern part of the Upper Rhine Graben.

The aim of this study is to test the suitability of fluvial sediments for OSL dating and to give a more reliable chronological interpretation for the Medieval fluvial activity in the southern part of the URG. This is part of an ongoing study investigating fluvial sediments from the Rhine system in the frame of the Heidelberg Drilling Project.

2 Geological setting

The Upper Rhine Graben is located between the cities of Basel and Mainz. Its extension has a length of about 300 km and a width of up to 36 km and about 20 km in the southern part and in the northern part, respectively. The altitude of the River Rhine decreases from about 280 m above sea level (asl) in the south near Basel to about 80 m asl in the north near Mainz. The River Rhine flows in numerous meanders northwards, which were partly regulated in the years between 1817 and 1874.

The maximum subsidence of the Quaternary is located in the Heidelberg Basin near to the city of Heidelberg. Bartz (1951, 1967, 1974)

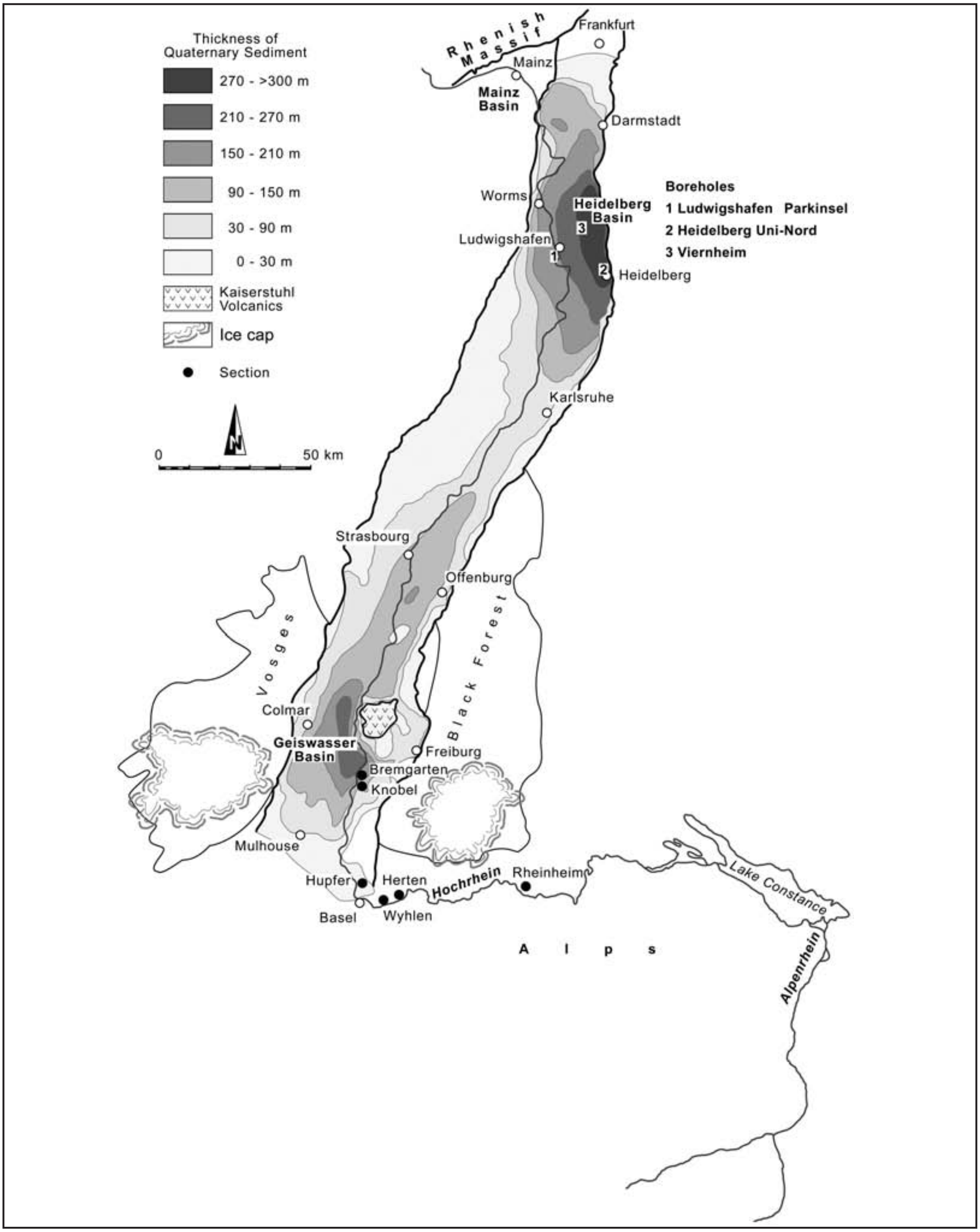

Fig. 1: Map showing the location of the Bremgarten section and the thickness of Quaternary sediments and the position of boreholes of the Heidelberg Drilling Project in the Upper Rhine Graben, modified after HAGEDORN (2004) and BARTZ (1974).

Abb. 1: Geographische Lage des Aufschlusses Bremgarten und der Bohrlokalitäten des Bohrprojektes Heidelberger Becken sowie Mächtigkeit der quartären Sedimente im Oberrheingraben modifiziert nach HAGEDORN (2004) und BARTZ (1974).

reported a thickness of more than 300 m for the Quaternary sequence and about 680 m for the Pliocene record. The Heidelberg Drilling Project including the up to 500 m long sediment cores from the sections at Heidelberg-UniNord, at Ludwigshafen-Parkinsel (Weidenfeller & Kärcher 2008) and at Viernheim, is currently aiming to reconstruct in detail the sediment archive of the basin fill (Fig. 1) (Ellwanger et al. 2005). A zone of elevated seismic activity is evidenced by the historical earthquakes of Basel Anno Domini (AD) 1021 and AD 1356. In the southern URG, tectonically active faults have caused offsets of up to 20 m during the Holocene (Hüttner 1991) resulting in a distinct terrace step east of the river Rhine. The higher level is called "Hochgestade" and the lower part between the step and the river is called "Tiefgestade". The difference in altitude between "Hochgestade" and "Tiefgestade" reaches several metres and has formed by a tectonically active fault propagating parallel to the present river course (Bram et al. 2005). Nivière et al. (2008) calculated maximum vertical movements along the faults not exceeding 1.0 mm/yr since the Middle Pleistocene. The current activity is concentrated along the westernmost faults. The coordinates of the section under investigation are H5309115 and R3394285 of the Gauss-Krüger system used in German topographic maps. The gravel pit Bremgarten GmbH is located about 150 m east of the river Rhine and situated in the lowermost part of the Lower Terrace termed "Tiefgestade" in the vicinity of the villages Bremgarten and Hartheim. About 7 m thick sand and gravel successions are exposed including pebbles originating from the Swiss Alps and the Black Forest. The upper part of the sediment succession is coarser than the lower part. A sand lens is covered by not well-sorted gravel about 2 m thick sand-rich. Up to three horizons can be distinguished and make three deposition events likely (Fig. 2, 3). Wood was collected for radiocarbon dating from the western wall about 3 m below surface. In 2006, two further trunks were exposed in the south wall and sampled for radiocarbon dating. The two trunks were located at the top of a sand layer which correlates to the base of a fining up cycle. The trunk has a north-south orientation, which is very likely the transport direction in the river at the time of deposition (Fig. 2). The lower part of the tree has still its bark, whereas the upper part of the trunk is bare of bark, most likely owing to erosion by water and sediment immediately after deposition of the trunk.

Sample BRE3 was taken 20 cm above the trunk and sample BRE4 was taken from about 20 cm below the trunk for OSL dating. Samples BRE1 and BRE2 were taken from a sand lens intercalated in light-greyish gravel from the eastern quarry wall in 2003 (Fig. 3). A piece of wood was intercalated in the sand lens, as previously described by Lämmermann-Barthel et al. (in press) and used for radiocarbon dating.

Massive Alpine sediment supply into the URG is unlikely for Medieval times, as lake Constance again formed as a sediment trap for the River Rhine (Wessels 1998). In the geological past, massive Alpine sediment supply probably resulted in a lateral movement of the Rhine over the whole southern URG (Lämmermann-Barthel et al. in press).

3 Luminescence dating

Luminescence dating of aeolian and fluvial sediments has proved to be successful where radiocarbon and other dating methods are not applicable (Frechen et al. 1997; Jain et al. 2003; Lian & Roberts 2006; Rittentour 2008). Since the late 1980s, luminescence dating of sediments has significantly been improved by the development of more light sensitive techniques such as green or blue optically stimulated luminescence (OSL) or infrared optically stimulated luminescence (IRSL) for monomineralic quartz or feldspar subsamples, respectively (Huntley et al. 1985; Hütt et al. 1988). A recent review about the lower and upper dating limit is found in Wintle (2008).

The basic principle of luminescence dating is solid state dosimetry of ionising radiation (Wintle 1997; Aitken 1998; Preusser et al. 2008).

The quartz signal saturates at lower doses than the feldspar signal. However, the advantage is often offset by the larger dose rates for the feld-

Fig. 2: Picture showing the position of the samples under study. A trunk is intercalated in sandy sediments (sand lense). The trunk was sampled for radiocarbon dating. Two samples were taken from sand about 20 cm below (LUM1220) and about 20 cm above (LUM1219) the trunk.

Abb. 2: Foto der Position der Probennahmepunkte im Aufschluss Bremgarten. Ein Baumstamm ist in die sandigen Sedimente zwischen geschaltet (Sandlinse). Das Holz wurde zur Radiokohlenstoff-Datierung beprobt. Jeweils eine Probe wurde 20 cm unterhalb (LUM1220) und oberhalb (LUM1219) des Baumstammes für OSL-Datierungen entnommen.

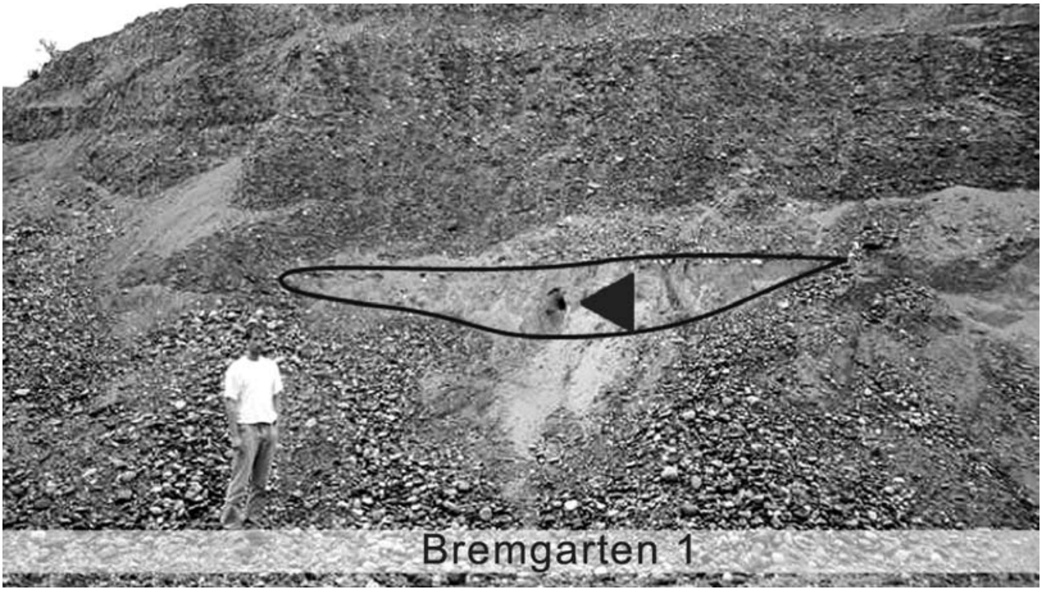

Fig. 3: Picture showing the position of sample BRE1. A second trunk was found 150 m in the north of the profile under study and sampled for radiocarbon dating.

Abb. 3: Foto mit der Position der Probe BRE1. Ein weiterer Baumstamm wurde etwa 150 m nördlich dieses Profils für eine Radiokohlenstoff-Datierung entnommen.

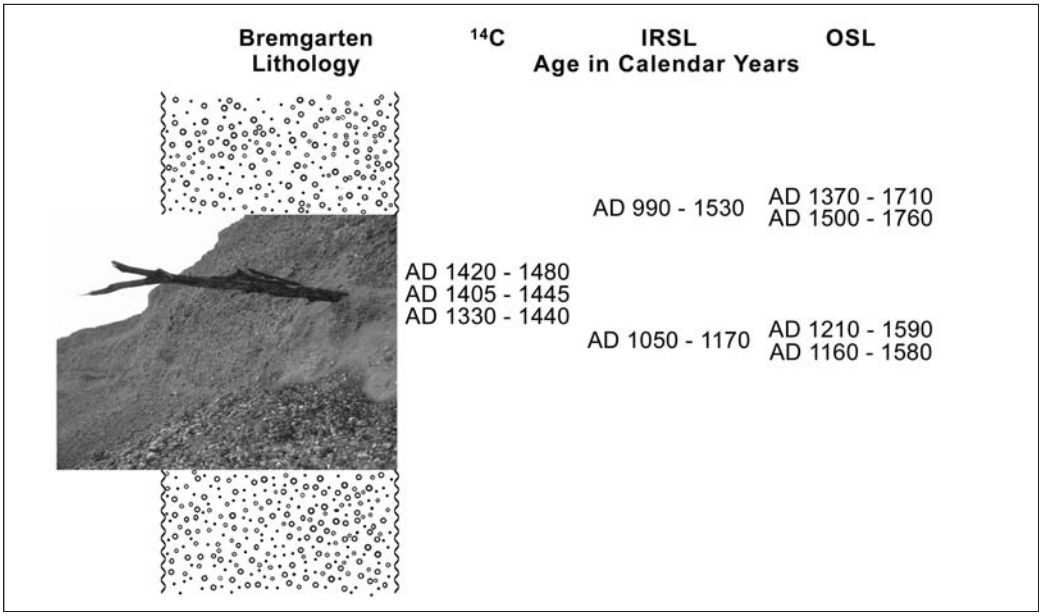

Fig. 4: Idealised sketch of the lithological units and the geological interpretation and position of radiocarbon and luminescence samples.

Abb. 4: Idealisierte Abbildung der Sedimentabfolge in Bremgarten mit geologischer Interpretation und Position der Radiokohlenstoff- und Lumineszenzproben.

spars owing to high potassium content within the feldspar mineral grains and athermal signal instability owing to anomalous fading (WINTLE 1973).

An important assumption of luminescence dating techniques is that the mineral grains were sufficiently long exposed to daylight/sunlight prior to deposition to reset the radiometric clock ("zeroing the luminescence signal"). The level of zeroing depends on the exposure time of the mineral grains to light, the available light intensity and the light spectrum. These parameters are strongly affected by fluvial sedimentary dynamics including water depth, sediment load, turbulence and turbidity, grain-size and transportation distance (RHODES & POWNALL 1994; FRECHEN 1995; MURRAY et al. 1995; WALLINGA et al. 2000; JAIN et al. 2003). In many fluvial environments the probability of complete zeroing of all sediment grains is low. JAIN et al. (2003), WALLINGA (2002) and SINGARAYER et al. (2005) pointed out that in contrast to aeolian sediment a distribution of values determined for fluvial deposits usually results in age overestimation, if equivalent doses are measured for samples containing a large number of grains. FUCHS et al. (2005) reported that quartz based equivalent dose (D_e) values yielded distinctly lower results than feldspar based D_e values for flood sediments giving evidence for better bleaching of quartz minerals extracted from the sediment. However, in large river systems the zeroing has been found to be more complete or nearly complete owing to the very likely multiple recycling of sediment during repeated phases of deposition and erosion (WALLINGA 2002). Most bleaching does occur when the grains are close to the water surface where the light intensity is greater and the light spectrum is more complete. Sediment from overbank deposits and scour pools are more likely to be suitable for luminescence dating. Samples taken from sediment of high-energy depositional environments like mass flow deposits or sediments from kames, are not suitable for luminescence dating (HÜTT & JUNGNER 1992). Partial bleaching of sediments is also attributed to flashy seasonal river flow (floods) associated with high-amplitude precipitation causing input from bank erosion (Jain et al. 2003). The existence of scatter in equivalent dose determinations is an indication for incomplete zeroing of the OSL signal. Grain-to-grain variations do produce scatter in single aliquot equivalent dose determinations (Lamothe et al. 1994; Murray & Roberts 1997; Olley et al. 1999). The detection of partial bleaching was previously investigated by using small single aliquots or single-grain methodology (Fuchs & Wagner 2003; Singarayer et al. 2005; Preusser et al. 2007) and different statistical approaches (Lepper et al. 2000; Bailey & Arnold 2006; Erkens et al. 2009). Following these studies, it appears to be mandatory to investigate a large number of single grains per sample from fluvial environments.

The first fluvial sediments from Germany, which were investigated by a dating approach combining IRSL, OSL and thermoluminescence (TL), were taken from sand layers of the Lower Terrace from the River Emscher (Frechen 1995). TL dating results showed large uncertainties most likely owing to incomplete bleaching prior to deposition; IRSL dating of potassium-rich feldspars showed a better

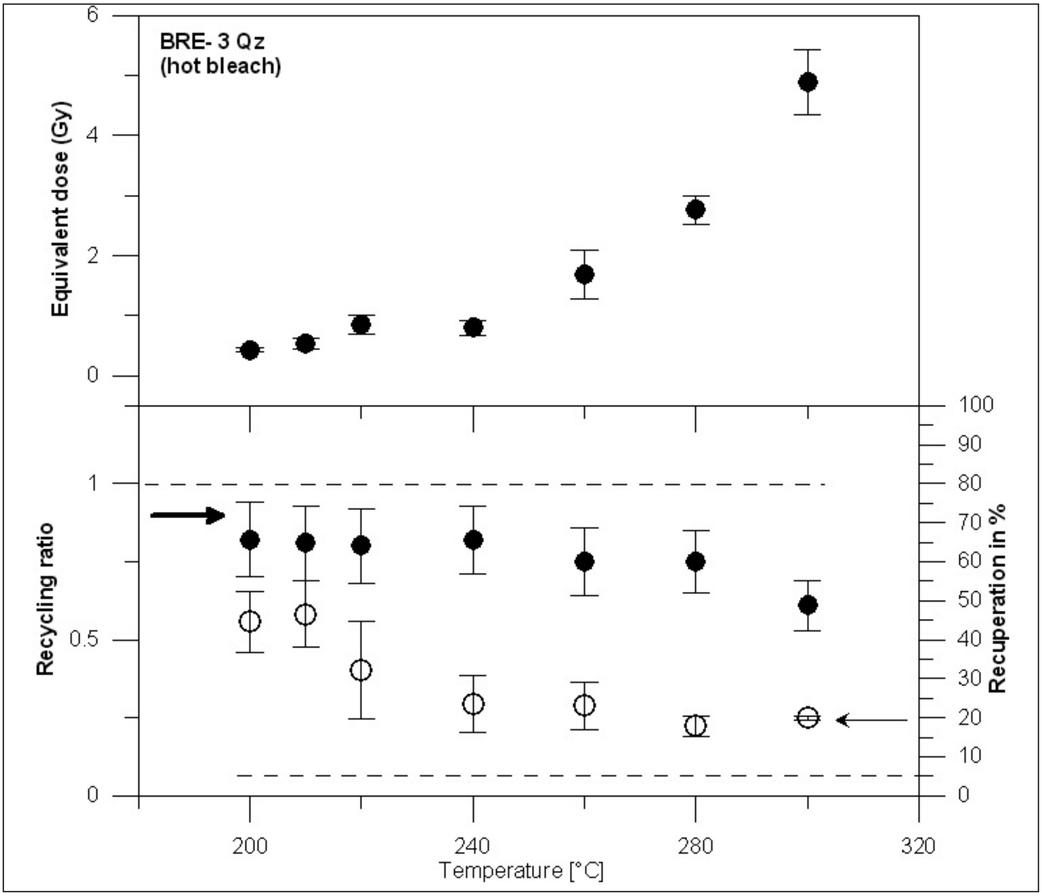

Fig. 5: Preheat plateau, recycling ratio and recuperation for sample BRE3 using quartz extracts and the hot bleach procedure.

Abb. 5: „Preheat plateau”, „Recycling Ratio” und „Recuperation” für Quarze der Probe BRE3 unter Anwendung des „Hot Bleach”-Verfahrens.

agreement with the geological age estimates. FRECHEN (1995) suggested to investigate 100-200 µm potassium-rich feldspar extracts to test the bleaching behaviour for different transmission wavelength.

Recent advances in instrumentation and measurement protocols have played a key role in enabling the dating of fluvial sediments. OSL dating of quartz has been significantly improved by single-aliquot regenerative (SAR) protocols (MURRAY & WINTLE 2000; WALLINGA et al. 2001). Sensitivity changes are monitored and corrected in the SAR protocol. This procedure allows the determination of equivalent dose by interpolation with a precision of up to 5 %.

Feldspar IRSL dating can be troubled by anomalous fading (WINTLE 1973) causing age underestimation. Anomalous fading is an athermal signal loss following irradiation and reflecting the instability of some of the electron traps. HUNTLEY & LAMOTHE (2001) pointed out that it is essential to determine the fading rate precisely and carried out fading experiments to correct the measured IRSL age estimates. However, age correction is problematic and a reliable procedure is still under discussion (AUCLAIR et al. 2003; LAMOTHE et al. 2003; HUOT & LAMOTHE 2003). There is a close relation between fading rate and geological provenance. HUNTLEY & LAMOTHE (2001) determined fading rates for North American sediments ranging from 2 to 10 % per decade (decade means a factor of 10 in time since irradiation). These fading corrections are restricted to the low-dose linear portion of the dose response and are not expected to be applicable to samples

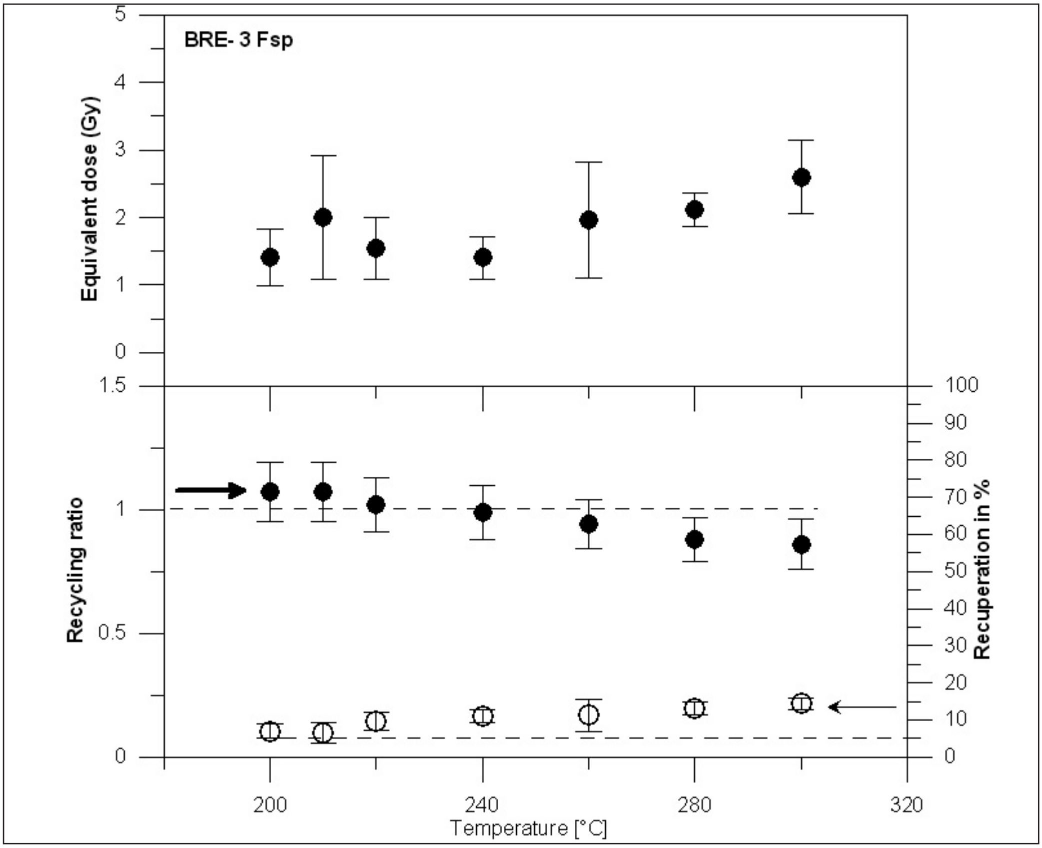

Fig. 6: Preheat plateau, recycling ratio and recuperation for sample BRE3 using feldspar extracts.

Abb. 6: „Preheat plateau", „Recycling Ratio" und „Recuperation" für Feldspäte der Probe BRE3.

older than ~20 - 50 ka. Fading corrections with a potential to be applicable over a much wider range are under discussion (Lamothe et al. 2003). Parts of the time-dependent signal from feldspars using pulsed stimulation show less fading than others (Tsukamoto et al. 2006) and thus possibly providing another way of dating potassium-rich feldspars. Preusser et al. (2007) reported that long-term fading has apparently no effect on potassium-rich feldspar specimens from the Swiss Alpine Foreland.
Natural ionising radiation includes alpha, beta and gamma irradiation released by the radioactive decay of the unstable isotopes of the ^{238}U, ^{235}U and ^{232}Th decay chains, ^{40}K and to a minor content ^{87}Rb and cosmic radiation. The dose rate depends on a number of external factors, some of them are even variable during burial time, like moisture, sediment thickness, grain-size, geochemical weathering of minerals or salts, mobilisation of clay minerals and radioactive equilibria/disequilibria of the decay chains and internal factors like the amount of ^{40}K in potassium-rich feldspars.

4 Experimental details and luminescence characteristics

Four luminescence samples were taken in light-tight metallic cylinders from sand lenses intercalated in gravel-rich fluvial deposits. The outer light-exposed part of the sediment was removed under subdued light at both ends of the cylinder. The sample preparation included sieving to separate the 100-200 µm or the 150-200 µm grain-size fractions, followed by

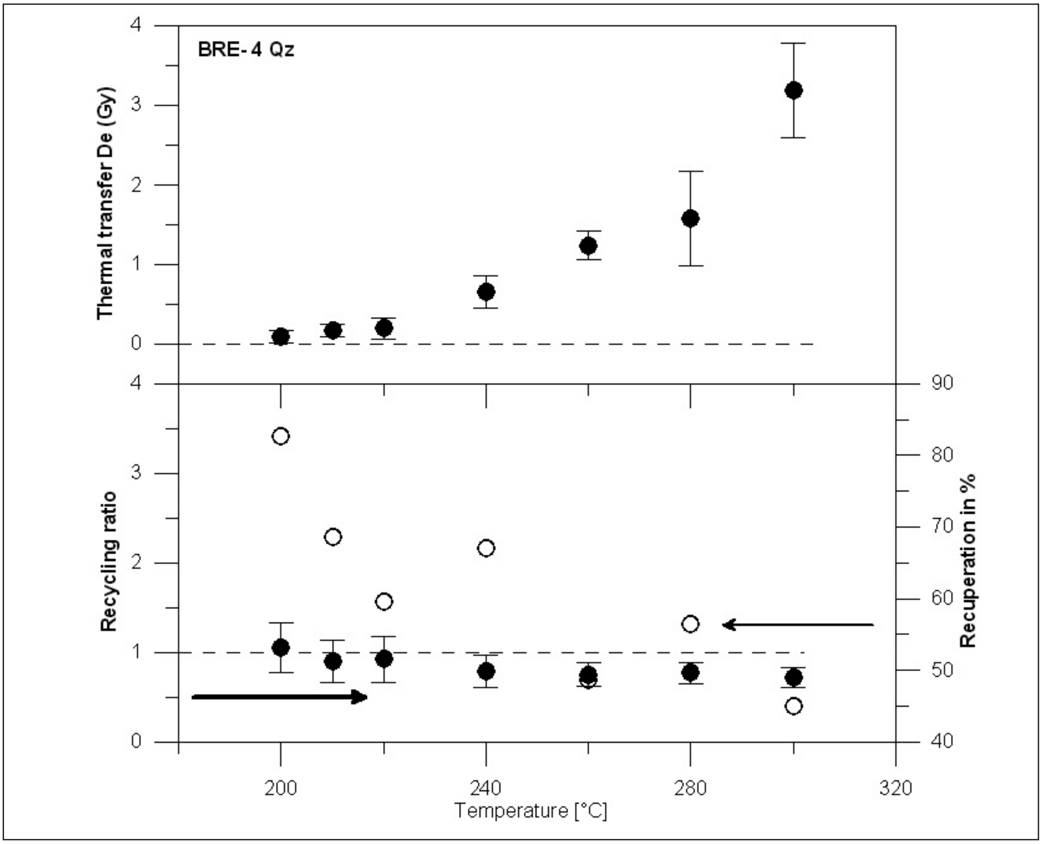

Fig. 7: Preheat plateau, recycling ratio and recuperation for sample BRE4 using quartz extracts.

Abb. 7: Preheat plateau", „Recycling Ratio" und „Recuperation" für Quarze der Probe BRE4.

removing the carbonates in 0,1 N hydrochloric acid, organic matter by 30 % hydrogen peroxide and clay particles by sodium oxalate. The sand-sized feldspar grains with densities lower than 2.58 g/cm³ were extracted using heavy liquids and the sand-sized quartz was extracted from the remaining fraction using heavy liquids of 2.62 g/cm³ and 2.70 g/cm³ densities. The quartz extracts were etched with 40 % hydrofluoric acid for 60 minutes to remove feldspars and sieved again with a 100 µm mesh or 150 µm mesh. The sand-sized quartz or feldspar grains were brought onto 0,9 mm steel discs (aliquots). IR stimulation was applied at the end of the quartz SAR protocol to test whether single aliquots show a contamination with feldspar deriving from inclusions after etching with hydrofluoric acid. Single aliquot regenerative-dose protocols were carried out for monomineralic quartz and feldspar extracts to determine the De values more precisely (MURRAY & WINTLE 2000; WALLINGA et al. 2000, 2001). All growth curves were fitted using a saturating exponential function.

A number of tests were carried out on both quartz and feldspar extracts to investigate the luminescence characteristics and to evaluate the suitability of the applied SAR protocol for the samples under study.

Preheat plateau

To determine appropriate preheat conditions for the determination of De values and to avoid thermal transfer effects, the variation of equivalent dose with preheat temperature was measured for both feldspar and quartz

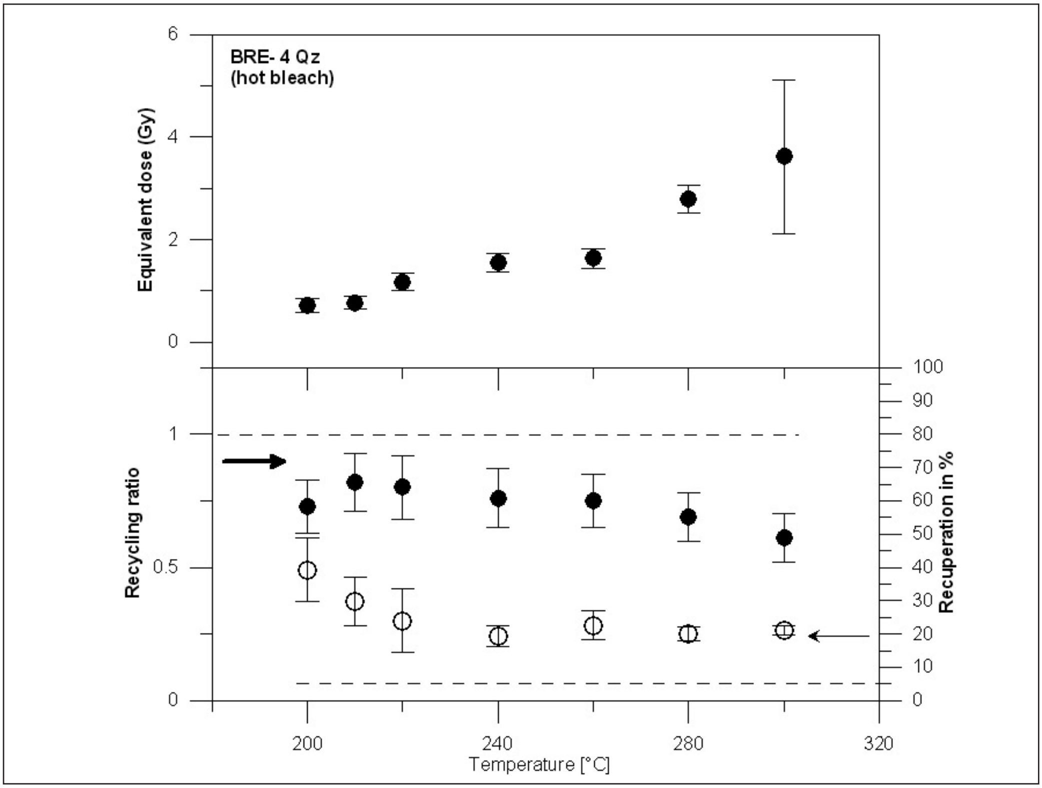

Fig. 8: Preheat plateau, recycling ratio and recuperation for sample BRE4 using quartz extracts. The hot bleach procedure was applied (MURRAY & WINTLE 2003).

Abb. 8: „Preheat plateau“, „Recycling Ratio“ und „Recuperation“ für Quarze der Probe BRE4 unter Anwendung des „Hot Bleach“-Verfahrens (MURRAY & WINTLE 2003).

extracts. A plateau of D_e values against preheat temperature for quartz and feldspar was determined using 10 seconds (s) preheats at 20°C intervals from 200 to 300°C (cp. MURRAY et al. 1997). Results were obtained from all samples. Examples of preheat plateau are given in Figs. 5-11. A preheat temperature of 210°C or 220°C for 10 seconds was used for natural and regenerative doses for quartz extracts and feldspar extracts.

Recycling ratio

Changes in the measured luminescence intensity with dose are known to occur in quartz and feldspar during single aliquot measurement procedures. Therefore a small test dose is given to each aliquot after the measurement of the natural or regenerated signal to determine sensitivity changes. The sensitivity correction is calculated by dividing the natural or regenerated IRSL or OSL intensity (Lx) by the test dose IRSL or OSL intensity (Tx). The recycling ratio (Rx/R1) is a test for the effectiveness of the sensitivity correction and determined by repeating the first dose point in the growth curve at the end of the measured cycle. The recycling ratio should be consistent with unity. MURRAY & WINTLE (2000) suggested that aliquots should be rejected if recycling ratios are outside 10 % of unity. However, MURRAY & WINTLE (2000) pointed out that the recycling ratio only tests whether sensitivity changes following laboratory measurements have been accurately corrected for. Figures 5-11 show plots of recycling ratios for samples BRE1-4 show-

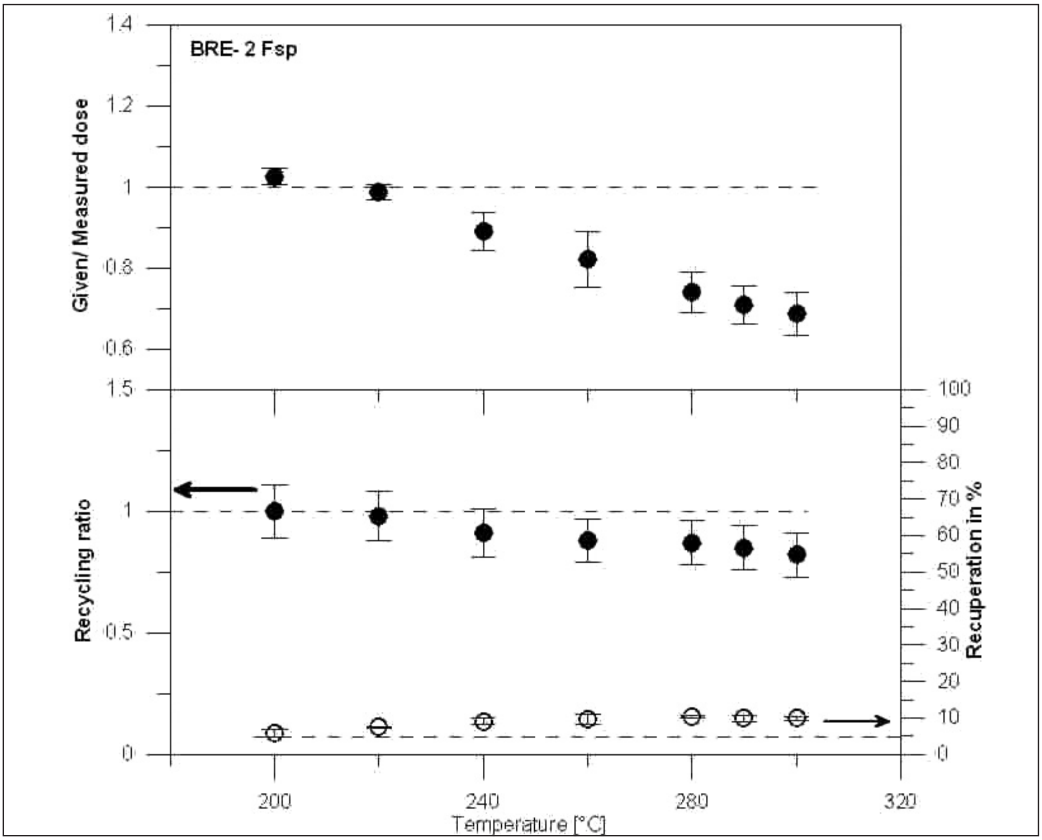

Fig. 9: Dose recovery test, recycling ratio and recuperation for sample BRE2 using feldspar extracts.

Abb. 9: „Dose recovery test“, „Recycling Ratio“ und „Recuperation“ für Feldspäte der Probe BRE2.

ing that for most of the samples the aliquots fall within 10 % of unity for the temperature range 200° to 220°C indicating that the SAR sensitivity correction is appropriate for these samples. Furthermore, a hot bleach treatment was used for the quartz extracts. After measurement of the response to the test dose, the aliquots were exposed to the blue diodes for 40 seconds whilst holding them at 280°C in order to reduce any build up of slow components in the OSL signal (Murray & Wintle, 2003). However, the recycling ratios concerning the hot bleach procedure for samples BRE3-quartz and BRE4-quartz fall only within 35 % of unity indicating that the sensitivity correction is problematic although the final OSL age estimates are within 1-standard deviation in agreement with independent age control. The SAR protocol for feldspar yielded recycling ratios within 10 % of unity for the preheat temperature range between 200° and 240°C.

Dose recovery test

A successful dose recovery test indicates that the SAR protocol produces internally consistent results for a sample and evaluates the creditability of the equivalent dose measured from a natural sample and so confirms that the applied SAR protocol enables to recover a known laboratory dose (Rhodes 2000). After bleaching the aliquots with a dr. hönle solar simulator, the aliquots were given a known laboratory dose close to the De value. The artificially dosed aliquots were then treated as "natural" in the SAR protocol (Table 1) to determine the De value (here:

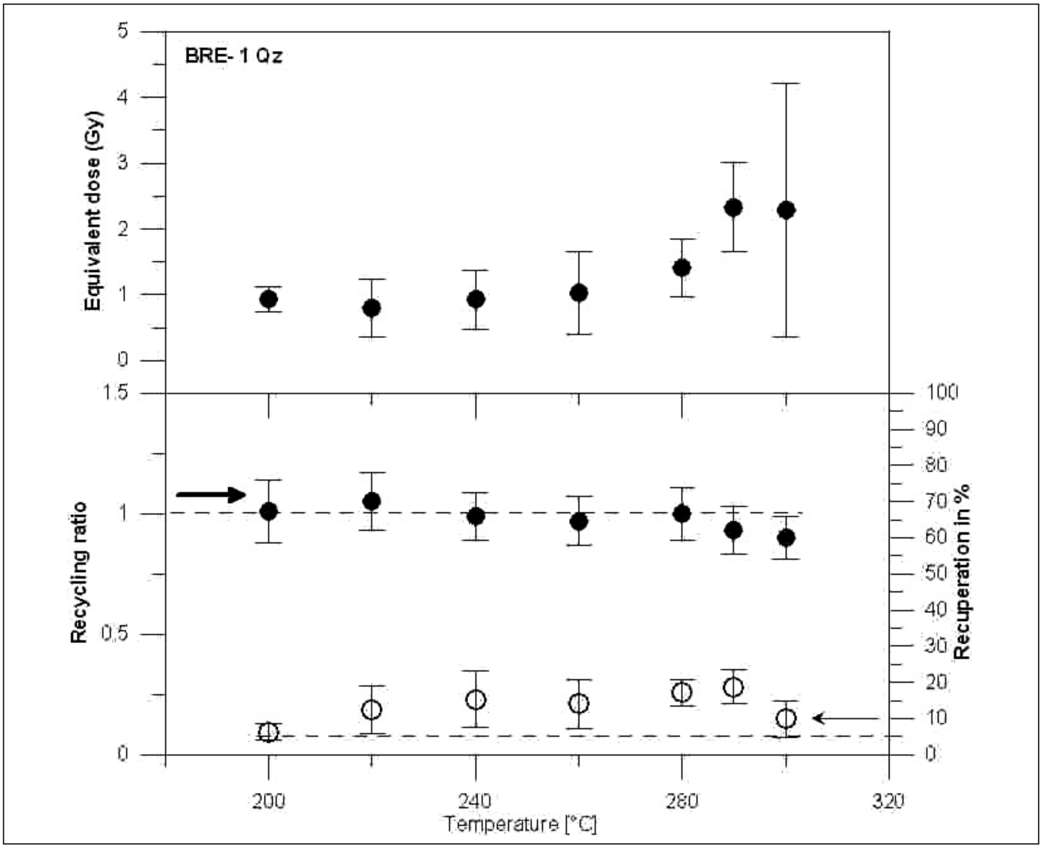

Fig. 10: Preheat plateau, recycling ratio and recuperation for sample BRE1 using quartz extracts.

Abb. 10: „Preheat plateau", „Recycling Ratio" und „Recuperation" für Quarze der Probe BRE1.

dose recovery). An example for dose recovery is given for sample BRE2-feldspar using a test dose of 1.0 Gy (Fig. 9). The dose recovery tests yielded the recovering dose values within 5 % from the given dose in the preheat temperature range 200°-220°C.

An example for thermal transfer is given in Figure 7. Sample BRE4-quartz seems to be stable for the temperature range between 200° and 220°C but shows an increasing amount of thermal transfer above 220°C. Recuperation is insufficient over the whole temperature range for sample BRE4-quartz (Fig. 8), whereas recuperation is less than 10 % and even less than 5 % over the temperature range between 200° and 240°C for sample BRE2-feldspar and BRE1-quartz (Fig. 9, 10). The hot bleach procedure gives a recuperation of >20 % over the temperature range from 200° to 300°C for sample BRE4-quartz.

Single-aliquot regenerative dose protocol

The single-aliquot regenerative (SAR) dose protocol was applied to determine the De values for feldspar and quartz (Murray & Wintle 2000; Wallinga et al. 2000, 2001; Wintle & Murray 2000). A dose response curve with typically three dose points is measured on a single aliquot by repeated irradiations, preheats and IRSL/OSL measurements. Sensitivity changes occurring due to laboratory heat treatment are monitored after each OSL measurement and corrected (Table 1). The weighted mean De value and the standard deviation were calculated for most of the samples

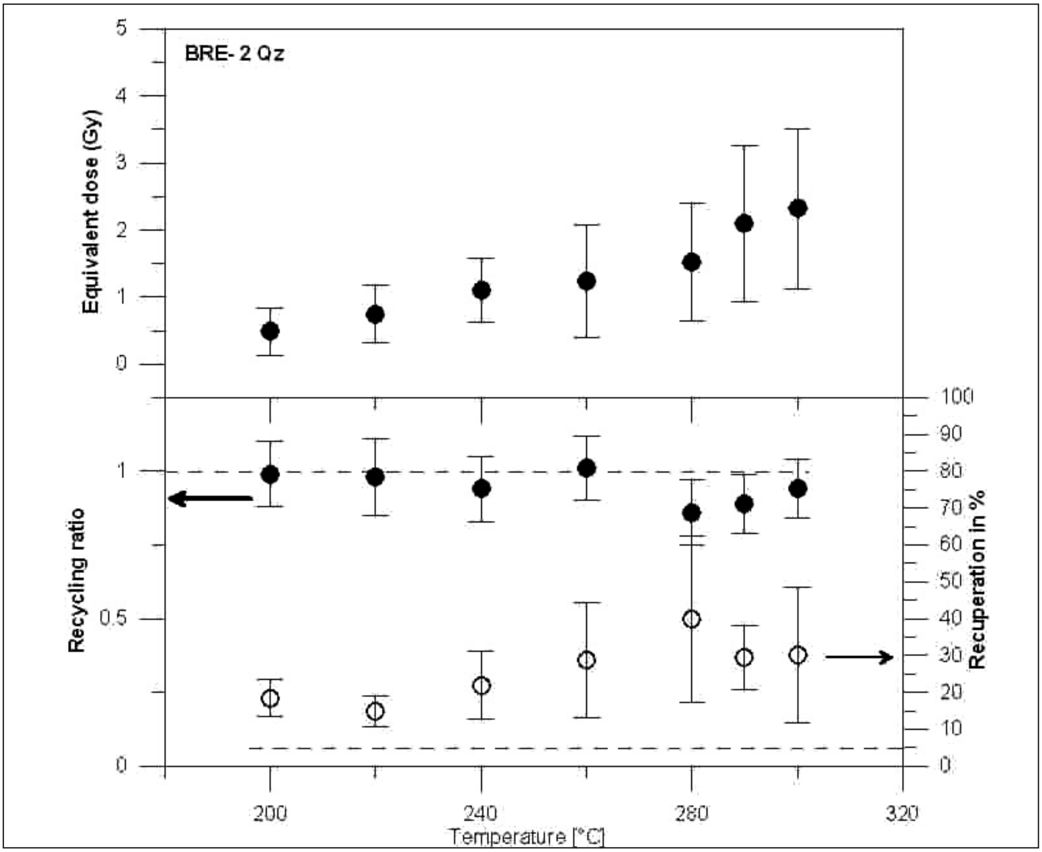

Fig. 11: Preheat plateau, recycling ratio and recuperation for sample BRE2 using quartz extracts.

Abb. 11: „Preheat plateau“, „Recycling Ratio“ und „Recuperation“ für Quarze der Probe BRE2.

from 24 aliquots for both feldspar and quartz grains. In general, aliquots were taken into account within a 3-sigma standard deviation and a recycling ratio between 0.8 and 1.2. Most of the dose points for the natural signal plotted between first and second artificial dose step. The hot bleach procedure resulted in two outliers (samples BRE3 and BRE4) with recycling ratios of 0.87. The IRSL signal was measured with a Schott BG39/Corning 7-59 filter combination between photomultiplier and feldspar extracts. A Schott U-340 filter with a detection window of 290–370 nm was placed for OSL measurements between photomultiplier and quartz extracts. Blue light emitting diodes were used for quartz stimulation.

Table 1: Single Aliquot Regenerative (SAR) protocol, as applied for quartz (Qz) (OSL stimulation) and feldspar (Fsp) grains (IRSL stimulation) (after MURRAY & WINTLE 2000; WALLINGA et al. 2000, 2001).

Tab. 1. SAR-Protokoll für Quarz (Qz) (OSL-Stimulation) - und Feldspatminerale (Fsp) (IRSL Stimulation) (nach MURRAY & WINTLE 2000; WALLINGA et al. 2000, 2001).

1. Preheat of Natural
2. IRSL decay of naturals for 300s at 50°C / OSL decay for 40s at 125°C
3. Test dose (10s)
4. Preheat of test dose of 210°C for 10s (Fsp), and 210°C for 0s (Qz)
5. Measurement of test dose (IRSL decay for 300s at 50°C for Fsp / OSL decay for 40s at 125°C for Qz)
6. Regenerative dose
7. Preheat of regenerative dose for 10s at 290°C (Fsp), 240°C or 260°C (Qz)
8. IRSL decay of regenerative dose for 300s at 50°C / OSL decay for 40s at 125°C
9. Test dose for 10s
10. Preheat of test dose at 210°C for 10s (Fsp), and 160°C or 210°C for 0s (Qz)
11. IRSL decay for 300s at 50°C / OSL decay for 40s at 125°C
12. Repeat step 6-11 for R2, R3, zero point and recycling point
    etc.

Equivalent dose determination was carried out using the software Analyst 6.0 (G.A.T. Duller, Aberystwyth, unpublished). Age calculation was applied by the software ADELE (M. Krbetschek, Freiburg, unpublished).

Dosimetry

As the outer shell of the feldspar minerals was not etched by hydrofluoric acid, alpha efficiency was estimated to a mean value of 0.2±0.1 for all feldspar samples (DULLER 1994). Dose rates for all samples were calculated from potassium, uranium and thorium contents, as measured by gamma spectrometry in the laboratory, assuming radioactive equilibrium for the decay chains. The following radioisotopes were measured: ^{234}Th, ^{214}Bi, ^{214}Pb and ^{212}Pb for uranium; ^{228}Ac, ^{208}Tl and ^{212}Pb for thorium and ^{40}K for potassium. An average internal potassium content of 12±0.5 % was applied for all feldspar samples (HUNTLEY & BARRIL 1997). Cosmic dose rate was corrected for the altitude and sediment thickness, as described by PRESCOTT & HUTTON (1994). The natural moisture content of the sediment was estimated between 10±2 weight % and 15±5 weight % for the samples.

5 Results

Dosimetric results, De values, IRSL and OSL age estimates are shown in Tables 2 and 3. Uncertainties are given in 1-sigma confidence interval. The total dose rates range from 2.21±0.22 to 2.53±0.11 Gy/ka and 1.60±0.05 to 1.70±0.06 Gy/ka for feldspar and quartz, respectively. The D_e values range from 0.6 to 1.1 Gy for quartz grains and from 1.6 to 2.0 Gray for feldspar extracts (Table 3), as determined by the SAR protocol (Table 1). Examples for the quartz and feldspar De-distributions of the single aliquot equivalent dose estimates and the radial plots of the same values are shown in figs. 12-15. They give an impression on the complete resetting of the OSL- signal prior to deposition. The radial plot (Fig. 15) displays an expanded De- distribution for the feldspar sample BRE4 indicating an insufficient bleaching of these minerals. In

Table 2: Dosimetric results, as determined by gammaspectrometry (ppm=parts per million; H_2O = moisture of sediment in weight %).

Tab. 2: Dosimetrische Ergebnisse durch Gammaspektrometrie bestimmt (ppm = part per million; H_2O = moisture of sediment in weight %).

Sample	LUM	Depth [m]	Grain Size [μm]	Uranium [ppm]	Thorium [ppm]
BRE 1	63	3.50	150-200	0.90±0.03	3.08±0.06
BRE 2	62	3.40	150-200	1.17±0.03	3.95±0.08
BRE 3	1219	3.00	150-200	1.13±0.01	3.78±0.03
BRE 4	1220	3.20	150-200	1.03±0.01	3.49±0.03

Potassium [%]	Cosmic [μGy/a]	H_2O [%]	Dose rate[1] [Gy/ka]	Dose rate[2] [Gy/ka]
1.29±0.02	120±12	10±2	2.39±0.10	1.60±0.05
1.28±0.03	120±12	10±2	2.53±0.11	1.70±0.06
1.18±0.01	120±12	15±5	2.23±0.22	1.62±0.16
1.21±0.01	120±12	15±5	2.21±0.22	1.61±0.16

contrast the quartz (Fig. 12) of BRE4 (Fig. 14) shows a nearly typical Gaussian distribution indicating that the mean equivalent dose is an appropriate estimate for the burial dose. OSL age estimates are used for chronostratigraphic interpretation only. IRSL age estimates are used for methodological comparison in this study only.

Two samples (BRE1 and BRE2) were taken from a sand lens at a depth of 3.40 m and 3.50 m below surface at the Bremgarten section in 2003. The IRSL age estimates gave 0.9±0.1 ka and 1.0±0.1 ka, whereas OSL age estimates yielded 1.9±0.2 ka and 1.4±0.1 ka. It is likely that the OSL age estimates for the two samples from Bremgarten are overestimated owing to the chosen preheat temperature of 260°C causing thermal transfer. Further experiments were unfortunately not possible owing to the lack of material. The samples BRE3 and BRE4 were taken in 2006 at the eastern wall of the gravel pit.

Sample BRE3 taken above a trunk, which was dated by radiocarbon, gave an OSL age estimate of 460±170 a, whereas the IRSL age estimate on feldspar extracts yielded 740±270 a. The hot bleach procedure yielded an OSL age estimate of 370±130 a, slightly age underestimated if compared with the radiocarbon ages on wood from the same profile. Age underestimation is also indicated by the dose recovery test. Sample BRE4 taken from below the trunk (Fig. 2) yielded OSL age estimates of 690±160 a and 600±190 a (hot bleach), which are in agreement within 1-sigma standard deviation with the results from sample BRE3. The IRSL age estimate is 890±60 a.

A trunk of an oak tree was sampled from the fluvial deposits at a depth of 3.00 m below surface from the Bremgarten section and studied by radiocarbon dating. The sand most likely correlates to the top of the second fining-up cycle, whereas the trunk postdates the deposition of the second fining-up cycle. The wood is intercalated between the sand layers of samples BRE1 and BRE2. The wood gave a conventional radiocarbon age of 510±45 BP (Hv 25350) resulting in a calibrated age of AD 1330–1440 (Table 4). The chronological results are stratigraphically consistent and in agreement with geological estimates. Two samples from a second trunk of the eastern wall taken in the same stratigraphic position and intercalating the sand layers of samples BRE3 and BRE4 gave radiocarbon ages of 440±45 BP and 485±45 BP resulting in calibrated radiocarbon ages of AD 1420-1480 and AD 1405-1445, respectively. The latter trunk from the eastern wall has about 40 tree-rings. Little variation in the thickness of the annual tree rings made the trunk unsuitable for dendrochronology (H.H. Leuschner, pers. com. 10/03/2008).

6 Discussion and Conclusion

In this study, we are confident that most of the quartz extracts yielded reliable results and uncertainties for D_e values. The resulting OSL age estimates are in excellent agreement with the radiocarbon ages indicating that in large fluvial systems the mineral grains are sufficiently zeroed prior to final deposition owing to several cycles of remobilisation. Furthermore, the results show that OSL methods are suitable for dating fluvial deposits. It is important to note that age overestimation owing to insufficient bleaching prior to deposition does not seem to be dramatic for the sediments under study. But OSL dating is not precise enough to set up an annual or decadal resolution for fluvial sediment records owing to the error between 5 and 10 % and the possibility of insufficient bleaching. IRSL dating yielded very likely age overestimation for the fluvial sands from the Bremgarten section, if compared with radiocarbon data and OSL dating results. Radiocarbon ages and IRSL age estimates are in agreement within 1-sigma standard deviation. From a stratigraphical point of view, the IRSL dating results are also reasonable and could give the true deposition age. However, fading correction was not applied for these feldspar extracts.

A similar behaviour was described for samples from historically deposited sediments from the Rhine-Meuse system in the Netherlands (Wallinga et al. 2001; Erkens et al. 2009). The likely reason for this age overestimation is insufficient bleaching prior to deposition. However, the results are in stratigraphic order and small offsets for the youngest samples indicate that insufficient bleaching does not seem to be dramatic for the samples from Bremgarten. It is still under discussion whether changes in sensitivity during the measurement of the natural signal or contamination of the quartz fast component OSL signal by a less stable slow component are responsible for the IRSL age overestimation alternatively OSL age underestimation. It remains risky to extrapolate the results of Holocene fluvial sediments to those fluvially transported and deposited during the Weichselian glaciation.

Heterogenous radiation fields including an unequal distribution of radioisotopes in the sedi-

Table 3: Equivalent dose (D_e) values in Gray (Gy) and luminescence age estimates in 1000 years (ka) for quartz and feldspar extracts using SAR protocols.

Tab. 3: Äquivalentdosis (De) in Gray (Gy) und Lumineszenz-Alter in 1000 Jahren (ka) für Quarz- und Feldspatextrakte mit einem SAR-Protokoll gemessen.

Sample	LUM	De value in [Gy]		OSL Age in [ka]	
		SAR-Fsp	SAR-Qz	SAR-Fsp	SAR-Qz
BRE1	62	2.1±0.1	3.0±0.3	0.88±0.06	1.9±0.2
BRE2	63	2.4±0.1	2.4±0.1	0.95±0.06	1.4±0.1
BRE3	1219	1.6±0.6	0.75±0.27	0.74±0.27	0.46±0.17
Hot bleach	1219		0.59±0.21		0.37±0.13
BRE4	1220	2.0±0.5	1.10±0.26	0.89±0.06	0.68±0.16
Hot bleach	1220		0.97±0.26		0.60±0.19

Table 4: Radiocarbon data.

Tab. 4: Radiokohlenstoff-Daten.

Hv	Sample	Material	Depth	$\delta^{13}C$	^{14}C Age	calibrated time interval
			m	‰	Years BP.	cal ...
25350	BRE 1	Holz	-	-26.5	510 ± 45	AD 1330 – 1440
25637	BRE 2	Holz	-	-24.9	440 ± 45	AD 1420 – 1480
25638	BRE 3	Holz	-	-25.3	485 ± 45	AD 1405 – 1445

ment and the occurrence of insufficient bleaching prior to deposition can cause problems for the determination of De values, if small aliquots or single-grain techniques are applied (Mayya et al. 2006). Titanite, monazite and zircon are uranium- and thorium-rich minerals resulting in radioactive hot spots in the sediments and thus giving reason for heterogenous microdosimetry, as previously described by using spatially resolved detection of luminescence (Greilich & Wagner 2006).

At about 2800 cal BP during the transition from Subboreal to Subatlantic, climate abruptly changed from a relatively warm and continental

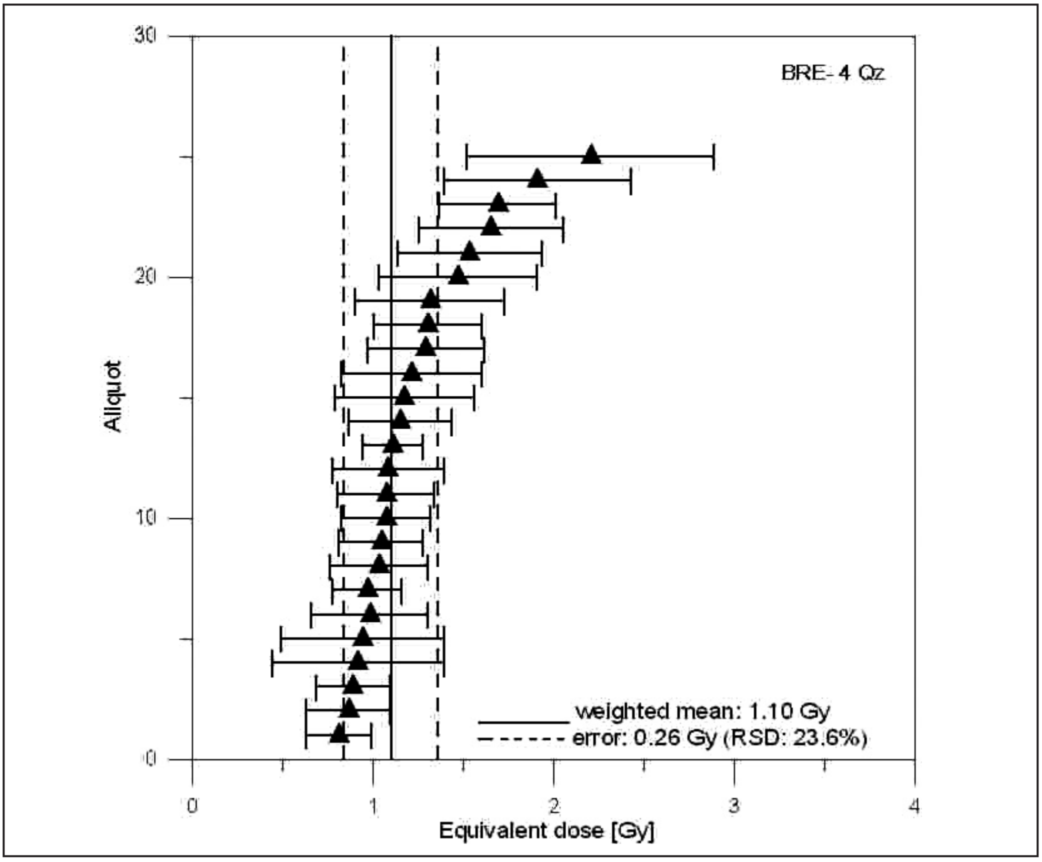

Fig. 12: Distribution of De values in increased order for quartz extracts of sample BRE4.

Abb. 12: Verteilung der De-Werte von Probe BRE4 (Quarz) in ansteigender Richtung angeordnet.

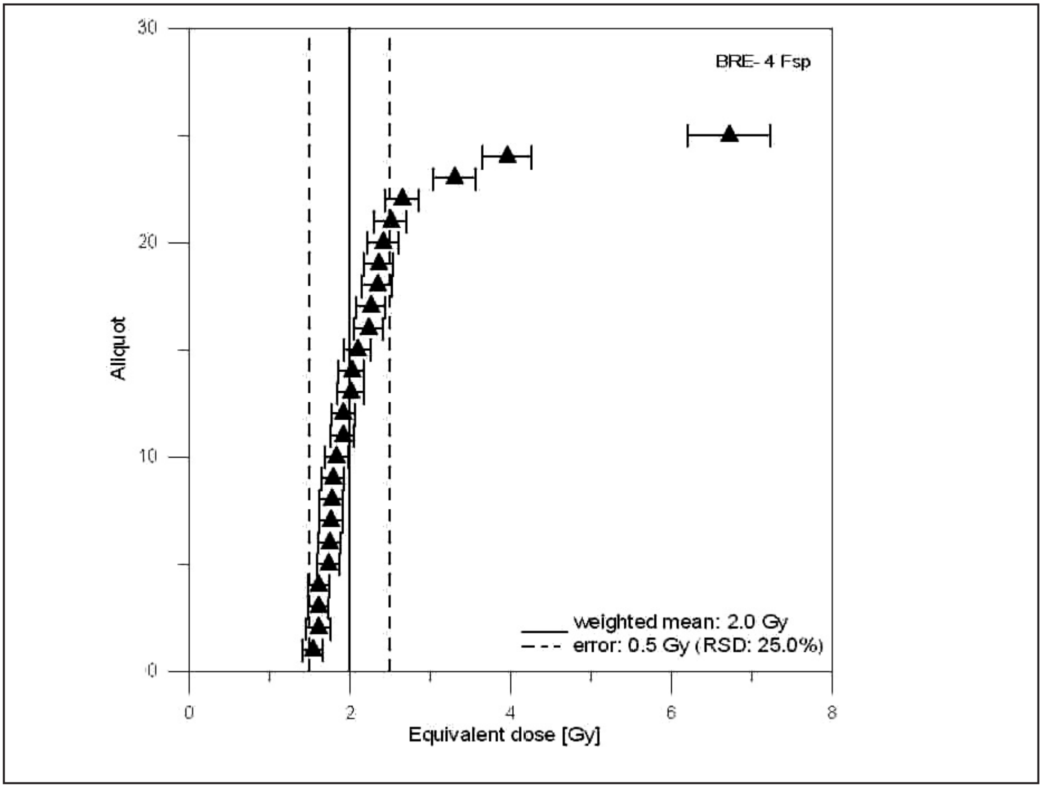

Fig. 13: Distribution of De values in increased order for feldspar extracts of sample BRE4.

Abb. 13: Verteilung der De-Werte von Probe BRE4 (Feldspat) in ansteigender Richtung angeordnet.

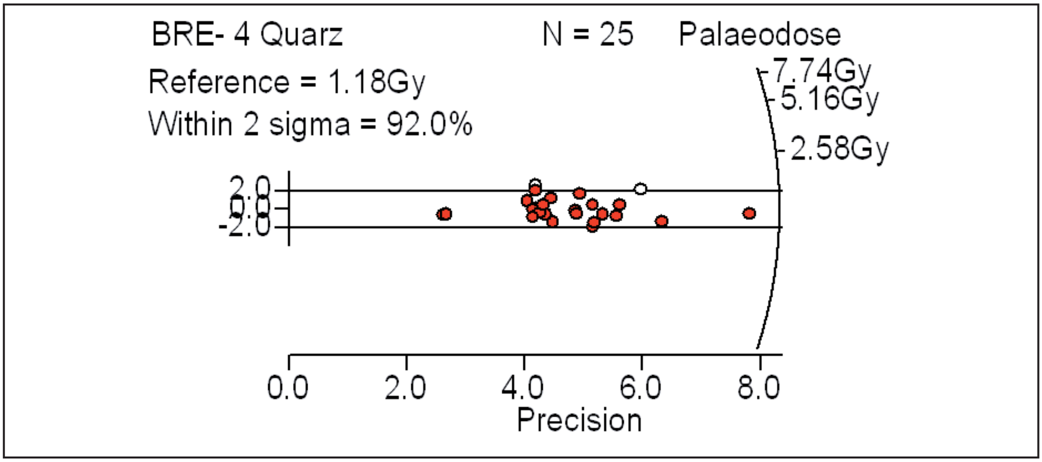

Fig. 14: Radial plot of De values for quartz extracts of sample BRE4. 92 % of the data points are within the 2-sigma standard deviation.

Abb. 14: Radialplot der De-Werte von Probe BRE4 (Quarz). 92 % der Datenpunkte liegen innerhalb der 2-sigma Standardabweichung.

climate to cooler and wetter conditions. The wetter climate in combination with intense human activity caused enhanced deforestation resulting in an increased erosion and run-off. Large amounts of waterlogged sediment were transported into the River Rhine causing a change in the meandering pattern of the river (Bos et al. 2008). Luminescence and radiocarbon dating results give evidence for a short period of major erosion and re-sedimentation of fluvial sediments from the “Tiefgestade” at the Bremgarten section between 500 and 600 years before present. This time period correlates with the beginning of the Little Ice Age lasting from about AD 1450 to 1850 (Bork 1989). Several severe floods occurred between 1500 and 1750, all correlated to the Little Ice Age; e.g. destruction of the village of Neuenburg AD 1525 (Glaser 2001). Furthermore, an extreme weather event resulting in a millenium flood is described for the year AD 1342. This flood caused a significant alteration of landscape such as up to 15 m deep incised canyons and reworking of 6-8 m thick fluvial sediments as debris flows in southern Germany (Bork 1989). The weather anomaly of AD 1342 could be very likely the reason for the fluvial dynamics including the aggradation of fluvial sediments more than 3 m thick in the southern URG. The latest radiocarbon data make a correlation of this major sediment mobilisation with the weather anomaly of AD 1342 unlikely.

Based on the radiocarbon data, the serious historical earthquake around the city of Basel in the year AD 1356 seems to be also unlikely to have triggered such a flood causing erosion and accumulation of about 3.50 m of gravel at the Bremgarten section. However, the OSL age estimates do not clearly exclude a deposition age around the weather anomaly of AD 1342 or the Basel earthquake in the year AD 1356 owing to the large error.

In the Netherlands, the youngest drift sands from the Maas River yielded a radiocarbon age of <1000 BP and an OSL age estimate of 0.6±0.1 ka (Bateman & van Huissteden 1999) and so might be correlated with the remobilised fluvial sediments from the southern URG.

The present data set leaves us uncomfortably with questions about the linkage of the aggradation periods with climate forcing of the Rhine system in southern Germany. The results contradict the cold climate origin of terrace sediments in the southern Upper Rhine Graben and open up new challenging questions. Methodological problems, such as the degree of bleaching during fluvial transport are still

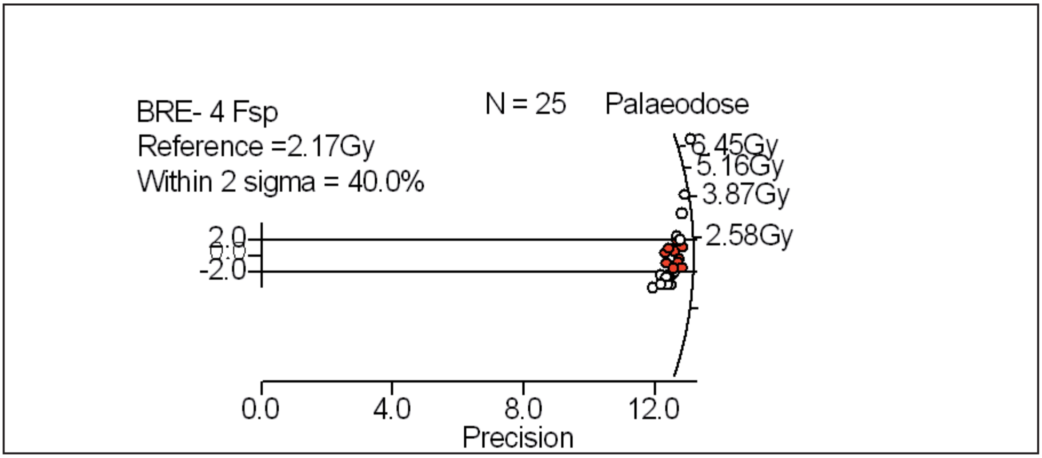

Fig. 15: Radial plot of De values for feldspar extracts of sample BRE4. 40 % of the data points are within the 2-sigma standard deviation.

Abb. 15: Radialplot der De-Werte von Probe BRE4 (Feldspat). 40 % der Datenpunkte liegen innerhalb der 2-sigma Standardabweichung.

difficult to determine, although age overestimation in large river systems seems to be not as dramatical as previously described. The quartz SAR protocol is very likely the best method to apply OSL dating to fluvial deposits. However, the IRSL age estimates, although not fading corrected, are also in agreement within the 1-sigma standard deviation, if compared to radiocarbon dates and so give also likely true deposition ages. This is part of an ongoing study investigating the timing of periods of increased aggradation in the Rhine system highlighting the response of a Central European large river system situated in a tectonically active region to environmental and climate change.

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