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Potential of a high-resolution DTM with large spatial coverage for visualization, identification and interpretation of young (Würmian) glacial geomorphology

a case study from Oberschwaben (southern Germany)

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Abstract: The German state of Baden-Württemberg has created a LiDAR-based digital terrain model (DTM) covering 36000 km² with a horizontal and vertical precision of 1 m and 0.15 m, respectively. This model is ideally suited for systematic geomorphological analyses as it is extremely accurate and allows reliable large-distance correlation of geological and geomorphological phenomena. Until recently, no available software could handle this amount of data in real time. One of us (T.M.) has developed a software (TerrainView) which allows the visualization of and navigation within the entire data set in nine levels of detail (in ortho and perspective view), while simultaneously offering effective tools for geomorphological and morphometric analyses. We present our first geomorphological studies based on this data set focussing on late Pleistocene glacial and proglacial/periglacial landforms in the Lake Constance/Oberschwaben area in southern Baden-Württemberg. In our study area we could identify and map a large variety of phenomena related to the last (Würmian) glaciation, including: subglacial basins with a wide variety of dimensions, outwash plains, moraines (end moraines, fragmentary moraines, kettled and hummocky moraines, micromoraines), subglacial and ice-marginal meltwater channels, eskers, drumlins and recessional terraces. Some of these features have been reported previously in literature, but others have not (or only partly) been recognized as such. Micromoraines might turn out an emerging new category of glacial features which typically are discovered at first in the DEM and subsequently verified in the field. The advantage of a geomorphological interpretation on the basis of a high-resolution DTM with large spatial coverage lies in the accurate identification of glacial and post-glacial morphological features and their correlation across large areas.

Visualisierung und Erkennung junger (würmeiszeitlicher) glazialer Landformen im großflächigen, hochauflösenden DGM: eine Fallstudie aus Oberschwaben (Süddeutschland)

Kurzfassung: Das Land Baden-Württemberg verfügt über ein flächendeckendes digitales Geländemodell (DGM) auf der Grundlage von LiDAR-Daten mit einer Genauigkeit von 1 m in der Horizontalen, 0,15 m in der Vertikalen und einem Gesamtumfang von 1 TB (*.txt). Dieses Modell ist für systematische geomorphologische Analysen hervorragend geeignet, doch scheiterte seine integrale Nutzung bisher an der Leistungsfähigkeit der verfügbaren Software, die ab Datenmengen von 50 GB stark abfällt. T. Müller hat eine Software entwickelt (TerrainView), die es ermöglicht, im gesamten Datensatz beliebig zu navigieren und Szenen in neun Auflösungsstufen verzögerungsfrei als Ortho- und Perspektivansicht zu visualisieren; geomorphologische und morphometrische Analysen können simultan durchgeführt werden. Wir stellen in dieser Studie erste Ergebnisse zu eiszeitlich überprägten Geländeformen im Raum Oberschwaben vor. Besonders im Verbreitungsgebiet des würmeiszeitlichen Rheingletschers ist es im DGM möglich, zahlreiche Ablagerungsformen zu identifizieren, mit hoher Präzision zu kartieren und teilweise auch geologisch zu interpretieren. Dazu gehören Zungenbecken verschiedenster Dimension, Aufschotterungsebenen, Endmoränen und Teilmoränen der Rückschmelzstadien in unterschiedlichem Erhaltungszustand, Mikromoränen, Esker, subglaziale und eisrandparallele Täler, Drumlins und Terrassenschachteln spät- bis postglazialer Flusssysteme. Manche dieser Erscheinungen sind aus der Literatur bekannt, doch ergeben sich durch die Möglichkeit, über große Entfernungen zu korrelieren, teilweise völlig neue Perspektiven in der geologischen Erkundung glazialer, periglazialer und postglazialer Landformen. Einige Phänomene wie zum Beispiel Mikromoränen konnten überhaupt erst im DGM als solche erkannt und dann nachträglich im Gelände verifiziert werden.

Keywords: *airborne LiDAR, high-resolution DTM, Würmian, glaciation, glacial landforms, Rhine glacier*

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1 Introduction

The LiDAR-based digital terrain model (DTM) of Baden-Württemberg ("Geobasisdatenmodell" [1], provided by Landesamt für Geoinformation und Landentwicklung (LGL, Stuttgart) has a resolution of 1 m in horizontal and 0.15 m in vertical direction covering 36000 km². This model is ideally suited for systematic geomorphological analyses as it is extremely accurate and allows reliable large-distance correlation of geological and geomorphological phenomena.

Comparable data sets are offered by a growing number of institutions. Evans (2012: 96) provides a selective overview of nationwide laser-based DEMs: 1 m resolution for parts of Austria; 2 to 5 m resolution for Belgium, the Netherlands and Alberta. LiDAR-based nationwide DTMs are offered by the National Land Survey of Finland (2x2 m grid, 14 cm vertical ground resolution; Sutinen, Hyvönen & Kukkonen 2013) and by the Geological Survey of Switzerland (swissALTI3D). Due to large differences in altitude, the DTM of Switzerland is based on a combination of LiDAR data, aerial photographs and stereo-correlation resulting in non-uniform resolution depending on the altitude (<2000 m: resolution 50 cm; >2000 m: resolution 1 to 3 m; Wiederkehr & Möri 2013). Most of the German states offer LiDAR-based DEMs with up to 1 m grids (www.geodatenzentrum.de/isoinfo/iso_rahmen.iso_div).

Geologic field work supported by high-resolution (≤1 m) large-area (>10000 km²) digital geomorphological exploration may benefit from this development but until now data processing and handling is slowed down or made impossible by the capacity of the currently available software. The main requirement for a software to cross this gap is instant processing of all types of visualization and morphometric analysis on all scales desired. An optimal working base would be a) a high-resolution DTM created from remote sensing procedures to identify a large range of phenomena, and b) a large area to follow these features tracing their real geological distribution.

To meet this requirement we developed TerrainView, a software designed to cope with the huge dataset covered by the LiDAR-based DTM of the state of Baden-Württemberg in south-western Germany. This study offers the results from a first test for geomorphic applications using glacial and proglacial/periglacial landforms produced during and after the Last Glacial Maximum (Würmian glaciation). In the process we discovered that in the special case of Würmian glacial phenomena the combination of high resolution and large area results in three advantages: 1) digital geomorphological mapping is at least as accurate as (and in some cases even surpasses) traditional field-based geomorphological mapping; 2) it is extremely fast, reliable and needs considerably less ground checks; 3) in the Oberschwaben area it allows recognition of additional glaciogenic phenomena hitherto not described in literature.

In the following we provide a brief description of the working features of TerrainView and present a state-of-the-art overview of the landforms related to the last glaciation in Baden-Württemberg. The potential offered by TerrainView is then explored in a series of case studies covering known features related to the Würmian glaciation as well as some new phenomena recognized from scrutinizing the DTM.

[1] http://www.lgl-bw.de/lgl-internet/opencms/de/07_Produkte_und_Dienstleistungen/Geodaten/; accessed 24.03.2014

2 Data source and software development

The digital terrain model of Baden-Württemberg ("Geobasisdatenmodell") is based on airborne LiDAR data and delivered as 1001 x 1001 m² tiles consisting of Gauss-Krüger coordinates and height values stored in text format (*.1m), where each data entry (easting, northing, height) covers 26 characters (26 Bytes). The complete dataset with 37676 tiles needs about 1 TB of disk space.

Commercial tools for DEM processing (e.g. ArcGIS, Rivertools, SCOP++) are able to handle only a limited subset of the dataset at once (roughly up to about 50 GB). For larger datasets, the performance decreases dramatically. Hence, interactive explorations and morphological studies for large areas, where the complete dataset must be available to ensure detailed height information throughout, become cumbersome.

For this reason we developed 'TerrainView' – an Open Graphics Library (OpenGL)-based platform for visualizing DTMs in orthographic and perspective projection with interactive navigation on large datasets and special tools for geomorphological analysis (http://go.visus.uni-stuttgart.de/terrainview). The key concept to master the huge dataset is to reformat it into a quadtree data structure with nine levels of detail (LOD) that decomposes the spatial domain recursively into uniform quads (tiles). Each quad has the same pixel resolution but a different pixel-size depending on the level of detail (LOD). The user can navigate among these levels of detail without delay. Memory usage is minimized as only these tiles that are currently visible and those that will become visible next are effectively loaded. This dynamic loading is thread-based to prevent jerking while navigating. Levels of detail are as follows: LOD 0: 256 m/pixel; LOD 1: 128 m/pixel; LOD 2: 64 m/pixel; LOD 3: 32 m/pixel; LOD 4: 16 m/pixel; LOD 5: 8 m/pixel; LOD 6: 4 m/pixel; LOD 7: 2 m/pixel; LOD 8: 1 m/pixel.

Reformatting into a quadtree data structure has to be done only once in a pre-processing step. We first set the base length of each tile to be 1024 x 1024 pixels. The root tile of the quadtree (LOD 0) encompasses the entire area of Baden-Württemberg (resolution: 256 m/pixel). The quadtree is built top-down; at level 8, each height value of the raw dataset

Fig. 1: Z-code coloured shaded relief of the study area. Geographic information and outlines of prominent glaciogenic features are compiled in complementary Fig. 2. White rectanlges: positions of case studies areas. Black area: Lake Constance. Inset lower left: position in Germany and in Baden-Württemberg. Orthoview; illumination: 90/33; vertical exaggeration: x 4; pixel size: 64 m.

Abb. 1: Farbhöhencodiertes Schummerungsmodell des Untersuchungsgebietes. Geographische Orientierungsmerkmale und die wichtigsten glaziogenen Strukturen sind in der komplementären Abb. 2 zusammengefasst. Weiße Rechtecke: Lage der nachfolgenden Abbildungen. Schwarz: Teile des Bodensees. Lage in Deutschland und Baden-Württemberg: siehe Übersicht unten links; Farbhöhencodierung: unten Mitte; Orthoprojektion; Beleuchtung: 90/33; vertikale Überhöhung: x 4; Pixelgröße: 64 m.

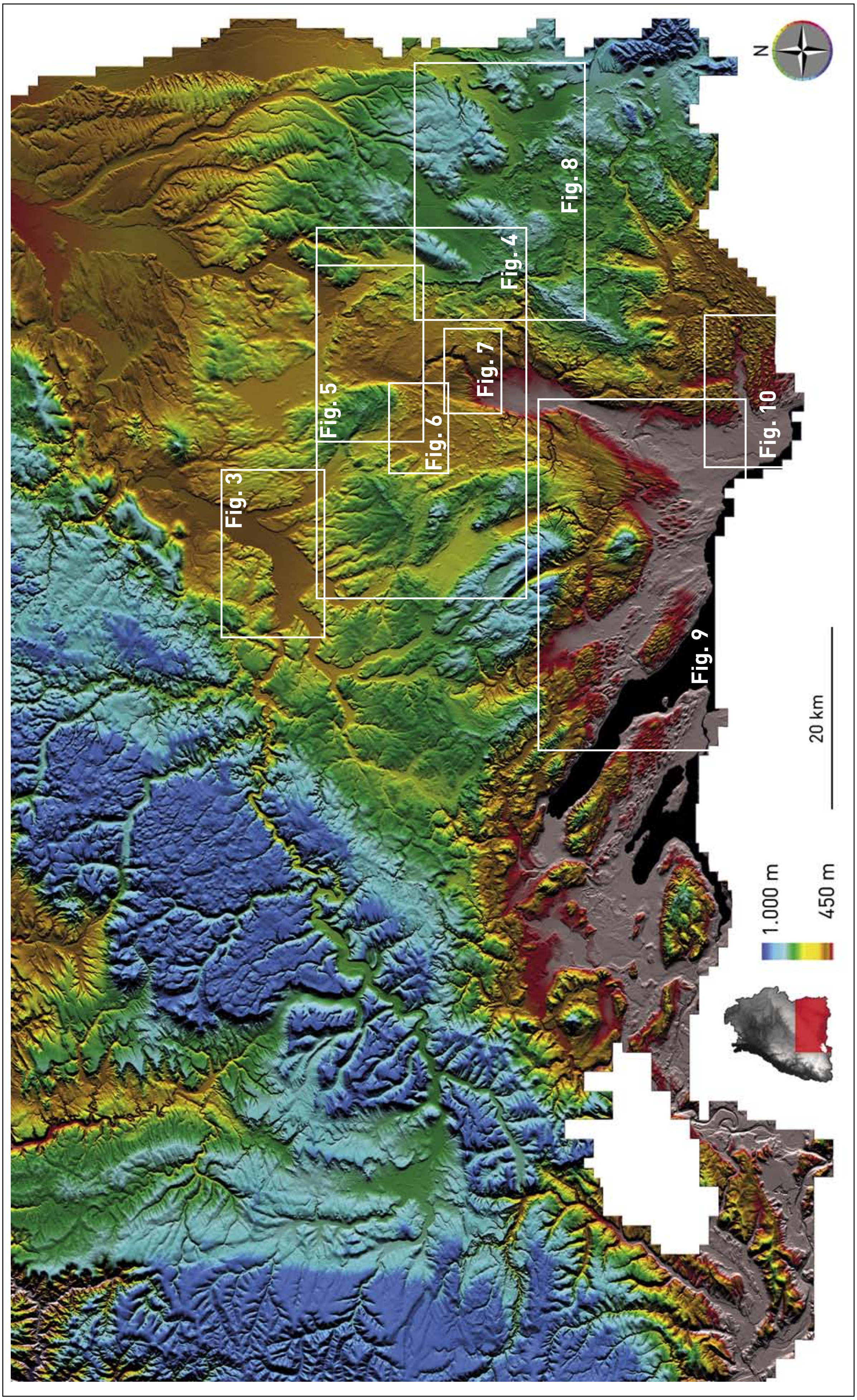
Fig. 3
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450 m
20 km

with corresponding easting-northing coordinates must be inserted into the correct tile. As this coordinate pair can be reconstructed from the quadtree structure, it is only necessary to store the height value. We use single precision floating point numbers (4 Byte) for the height value reducing the size of the dataset to about a sixth. Each lower level of the quadtree follows from the higher level by integrating 4 neighbouring height values until ending up at the root level. Despite an overhead through storing lower resolutions the entire dataset finally reduced to 189 GB in binary format.

Terrain visualization in orthographic and perspective projection is realized directly on the graphics board using OpenGL[2] shading language (GLSL). Colour coding, relief shading and other visualization features are calculated at interactive frame rates without any additional preprocessing steps. Light direction and vertical exaggeration can be instantly adapted to produce optimal shading and relief effects. Gradients are available in normal and inverse mode and can be exaggerated to enhance steepness; contours can be spaced on individual criteria and draped as overlays on all types of view. Morphometric data (longitudinal sections, cross-sections) can be derived placing polygons and/or serial sections.

TerrainView is based on Qt[3] and thus is platform-independent. All parameters of a chosen scene can be saved as Qt scripts for rapid reproducibility; all types of views can be exported as high resolution PNG images.

3 Outline of glaciations and glacial landforms in Baden-Württemberg

In Baden-Württemberg the Lake Constance/Oberschwaben region is particularly well suited for testing the visualization and mapping potential of Pleistocene landforms in a large DTM. Pleistocene landforms have been overprinted by advances of the Alpine Rhine glacier into the foreland. According to Ellwanger et al. (2011b) the earliest glaciations occurred during the Middle Pleistocene (Hoßkirch glaciation, Riß glaciation). They extended far beyond the borders of the late Pleistocene (Würmian) Rhine glacier (Ellwanger et al. 2011b, fig. 1). The Würmian glaciation episode (Birrfeld glaciation in Switzerland; Graf 2009, Keller & Krayss 2010), originally defined by Penck & Brückner (1909), lasted from 115 ka to 11.6 ka (Menning & DSK 2002, Litt et al. 2005) and consisted of three pulses of glacier advance centred around 105, 65, and 25 ka (Preusser et al. 2011). The last advance was strongest producing an ice sheet extending more than 60 km into the north Alpine foreland (Ehlers & Gibbard 2004). According to Preusser et al. (2011) in the area of the present study the ice cover lasted from 26 to 17.5 ka. In Bavaria, piedmont glaciers had vanished around 16 to 15 ka (Reuther et al. 2011). We present our first geomorphic studies based on the "Geobasisdaten" set focussing on Würmian glacial (Habbe et al. 2007) and proglacial/periglacial (French 2007) phenomena as only these youngest features are clearly recognizable in the DTM. With few exceptions (see chapters 4.1 and 4.8), morphologic features from older glaciations cannot be recognized in the model.

In the north Alpine foreland a comprehensive study by Salcher, Hinsch & Wagreich (2010) analysed glacial landforms based on LiDAR imagery in an area of 15 x 10 km corresponding to the frontal parts of the latest Pleistocene (Würmian) Salzach glacier 20 km north of Salzburg (Austria). According to these authors glacial landforms recognizable in a high-resolution DTM comprise the following phenomena: subglacial basins, outwash plains, continuous moraines, fragmentary recessional moraines, kettled and hummocky moraines, eskers, kames, kame terraces, subglacial channels, drumlins, and recessional terraces. In the following, usage of these terms is based on definitions present-

2 http://www.opengl.org/; accessed 24.03.2014

3 http://qt-project.org/; accessed 24.03.2014

Fig. 2: Shaded relief of same scene as in Fig. 1 with geographic information and outlines or locations of prominent glaciogenic features. Inset lower left: position within Baden-Württemberg. Light blue: Lake Constance. Numbering follows palaeogeographic belts from distal to proximal (North to South) and internally from West to East.

***Moraines**: Dotted yellow lines: end moraines clearly discernible in DTM. REM: relic of Riß end moraine; OWEM: outer Würmian end moraine. BiBi: Binzen bifurcation, overlap of the northern Schussen lobe (OWEM-SL) on the eastern Leutkirch lobe (OWEM-LL) of the Rhine glacier shows that the Schussen lobe persisted longer than the Leutkirch lobe; IWEM: inner Würmian end moraine; KS ("Konstanzer Stadium"): last stationary episode during glacial retreat marked by erosional features or fragmentary moraines.*

***Subglacial basins and outwash plains**: Riedlingen plain (1), Federsee plain (2), Laupheim plain (3), Wurzacher Ried (4), Bibertal (5), Pfrunger Ried (6), Altshausen basin (7), Upper Schussen basin (8), Aach plain (9), Zeller See (10), Überlinger See (11), Salem valley (12), Föhrenried (14), Lower Schussen basin (15).*

***Drumlins and other glacial to periglacial features**: The area between the inner Würmian end moraine (IWEM) and the "Konstanzer Stadium" (KS) is a domain of radially elongated high-convexity drumlins locally (west of Ravensburg) grading into low-convexity equivalents. The Gehrenberg hill (13) is an abraded buttress of late Miocene Upper Freshwater Molasse rocks. Recessional terraces are best preserved in the Lower Argen Valley.*

Abb. 2: Schummerungsmodell derselben Szene wie in Abb. 1 mit geographischen Orientierungsmerkmalen und wichtigen glaziogenen Strukturen. Lage in Baden-Württemberg: siehe Übersicht unten links. Hellblau: Teile des Bodensees. Die Nummerierung folgt den paläogeographischen Gürteln von distal zu proximal (Nord nach Süd) und innerhalb dieser Gürtel von West nach Ost. In diesem Maßstab sind folgende glaziale Landschaftsformen deutlich zu erkennen:

***Moränen**: Endmoränen (gelbe punktierte Linien): Rißendmoräne (REM); Äußere Würmendmoräne (OWEM); Bifurkation von Binzen (BiBi): der Überschneidungskontakt zwischen der Endmoräne des nördlichen Schussen-Lobus (OWEM-SL) und dem östlichen Leutkirch-Lobus (OWEM-LL) belegt, dass der Schussen-Lobus länger aktiv war als der Leutkirch-Lobus; Innere Würmendmoräne (IWEM); Endmoräne des „Konstanzer Stadiums" (KS).*

***Subglaziale Becken und Schotterebenen**: Riedlinger Ebene (1), Federsee-Ebene (2), Laupheimer Ebene (3), Wurzacher Ried (4), Bibertal (5), Pfrunger Ried (6), Altshausener Becken (7), Oberes Schussenbecken (8), Aach-Ebene (9), Zeller See (10), Überlinger See (11), Salemer Tal (12), Föhrenried (14), Unteres Schussenbecken (15).*

***Drumlins und weitere glaziale bis periglaziale Strukturen**: Der Raum zwischen der Inneren Würmendmoräne (IWEM) und der Endmoräne des „Konstanzer Stadiums" (KS) zeigt radial ausgerichtete, vorwiegend hochkonvexe Drumlins, die lokal (westlich von Ravensburg) in flache, stark ausgelängte Drumlins übergehen. Der Gehrenberg (13) ist ein vom Gletscher überschliffener Ausbiss von spätmiozäner Oberer Süßwassermolasse. Spätglaziale Terrassenschachteln sind im unteren Argental sehr gut erhalten.*

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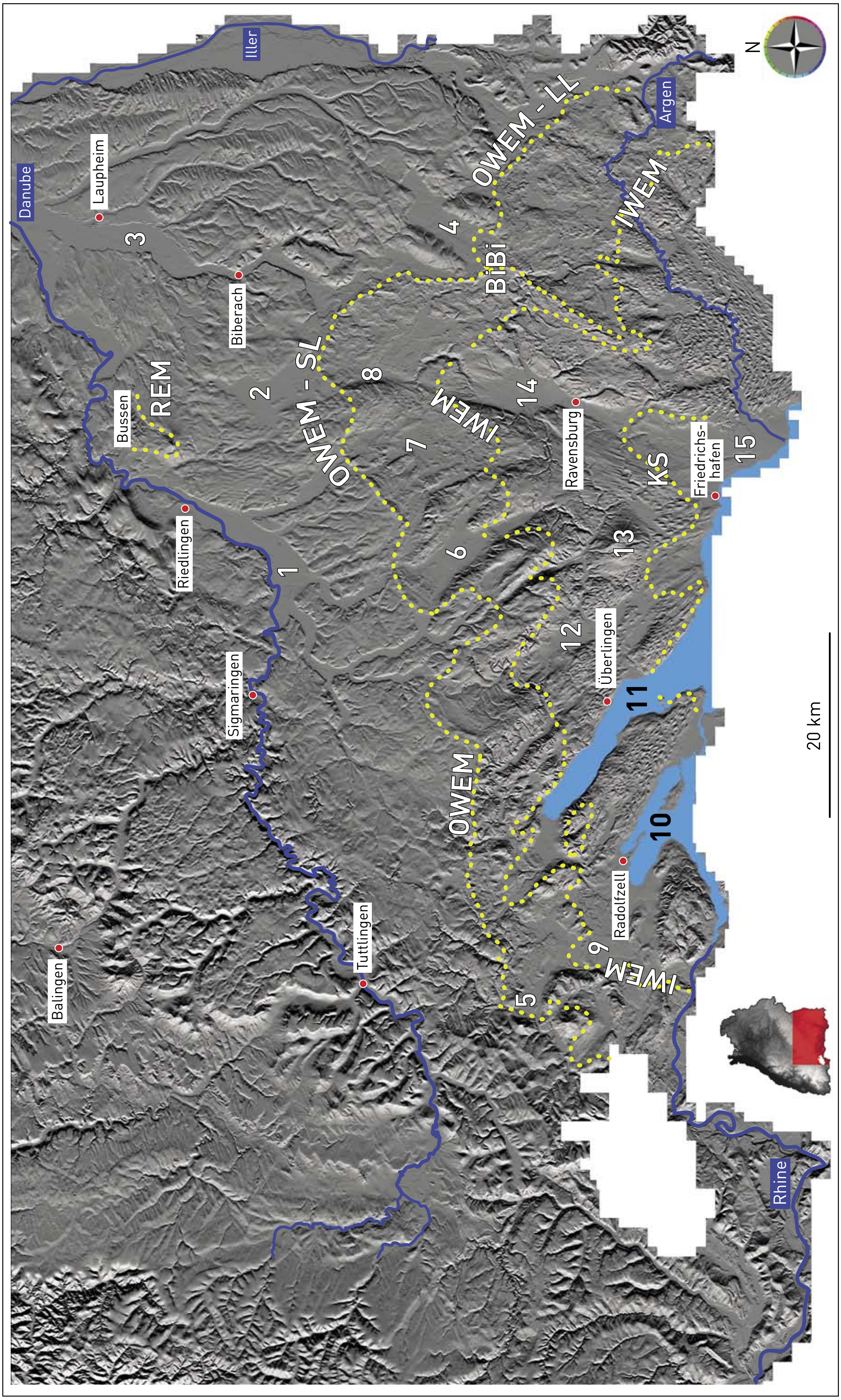
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ed by Brodzikowski & van Loon (1991), Schaefer (1995), Menzies (1996), Ehlers (1996) and Benn & Evans (1998). In comparison to DTMs, conventional topographic maps do not provide sufficient information to identify such features without ground check.

However, after more than a century of research the distribution of most of these units is well known from geological mapping although there has been a certain tendency to highlight moraines, drumlins, and outwash plains over other glacial phenomena. For the area of south-western Germany and adjoining areas Penck & Brückner (1909), Hantke (1978, 1980), Schreiner (1974, 1992a, 1992b), Ellwanger et al. (1995), Jerz (1995), Schaefer (1995), Eberle et al. (2007), Zaugg et al. (2008), Doppler et al. (2011), Ellwanger et al. (2011a, 2011b), Hantke (2011), Preusser et al. (2011) and van Husen & Reitner (2011) have presented contemporary state-of-the-art compilations. Information on the extent and amount of the glaciation of Switzerland during the Last Glacial Maximum is provided in great detail by the map published by Bini et al. (2009), which also covers adjacent areas in south-western Germany. Similar maps exist for the reconstruction of the ice surface geometry and flowlines in the Central Swiss Alps (Florineth & Schlüchter 1998) and for the Eastern Alps during the last glaciation (van Husen 1987, de Graaff, de Jong & Seijmonsbergen 2007, Rupp, Linner & Mandl 2011).

General information on the study area is condensed in Figs. 1 and 2. Fig. 1 gives an overview in coloured shaded relief while Fig. 2 provides corresponding geographic data and the outlines of major late Pleistocene landform units on the background of a grey shaded relief map. In the following, a series of case studies demonstrates the potential of high-resolution digital mapping.

4 Case studies of Würmian glacial landforms identified from the DTM

The wealth of observations on Würmian glacial landforms is such that neither a systematic nor a thematic approach is apt for presentation in an overview. We therefore decided to show our results in nine case studies highlighting important features. Thus, the order of subchapters tracks a path through the DTM starting in the North and ending in the South. For a geographical overview and positions of case studies see Fig. 1.

4.1 Continuous major moraines

Continuous end moraines are well defined from geological mapping on scale 1:25000. The oldest end moraines (Riß glaciation and older) cannot unambiguously be identified in the DTM (with the exception of a Rissian end moraine relic flanking the Bussen hill near Riedlingen labelled “REM” in Fig. 2). In contrast, moraines corresponding to the Last Glacial Maximum (outer Würmian end moraine, label OWEM in Fig. 2) can be recognized and mapped in detail, especially in the north-eastern sector of the study area. Accuracy of delineation equals or surpasses geological mapping on the scale of 1:25000. In the western part of the study area end moraines are less well preserved but still can be traced throughout the DTM. The same applies for the inner Würmian end moraine (label IWEM in Fig. 2). Supposedly this difference in preservation is a result from steeper gradients at the outer margins of subglacial branch basins (compare Fig. 1).

The outer Würmian end moraine possesses a conspicuous bifurcation located at the hamlet of Binzen (BiBi in Fig. 2). There, the outer Würmian end moraine of the northern Schussen lobe (label OWEM-SL in Fig. 2) of the Rhine glacier crosscuts the end moraine of the eastern Leutkirch lobe (label OWEM-LL in Fig. 2) thus indicating a longer ice activity of the northern Schussen lobe (OWEM-SL); details are explained in Fig. 8.

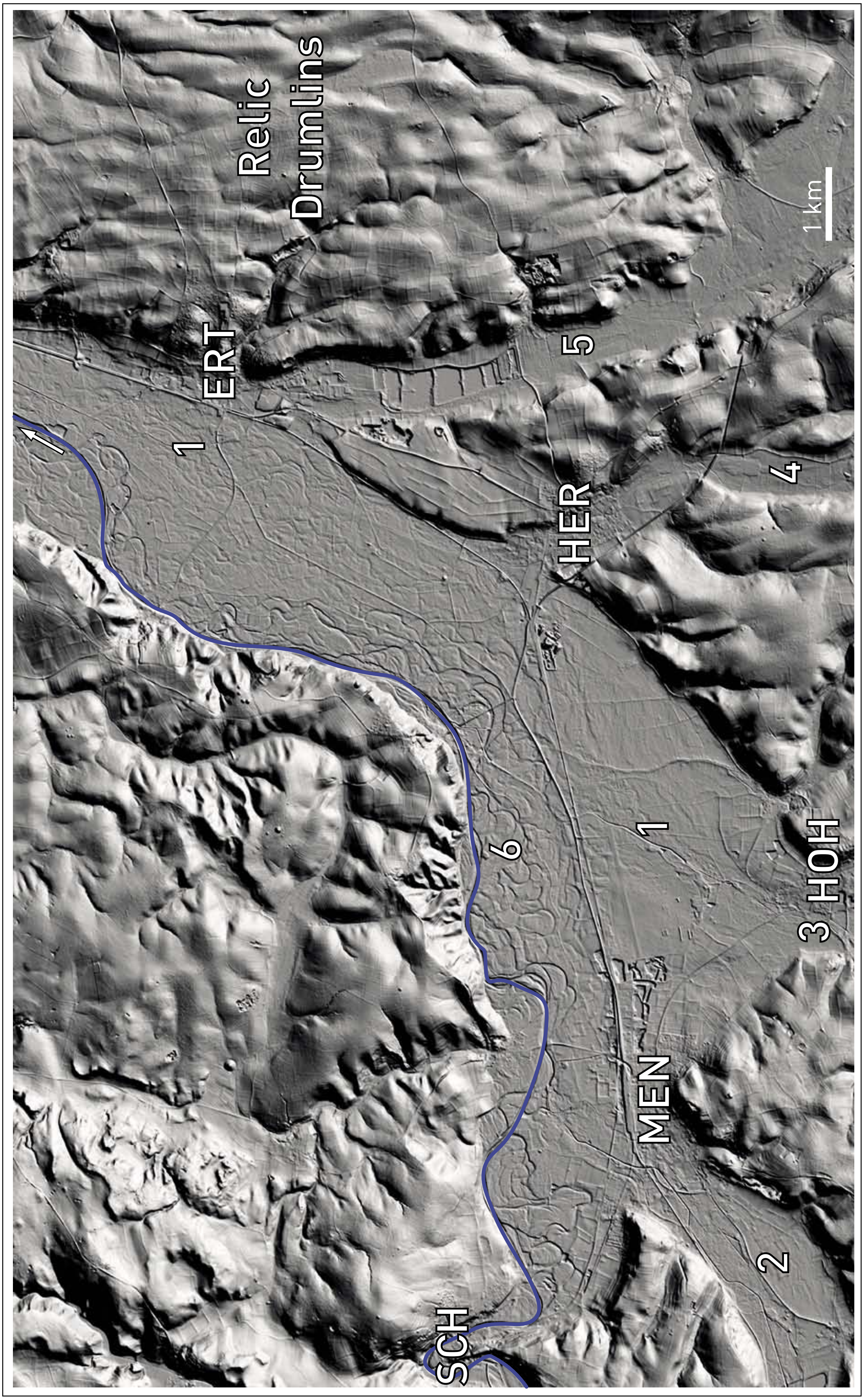
Prior to final glacier retreat into the main Lake Constance tongue basin a short-term stationary episode (“Konstanzer Stadium” sensu Schreiner 1974; label KS in Fig. 2) produced erosional scarps. These can be traced throughout the DTM as a boundary between well-preserved (north of KS line) and partly truncated (south of KS line) drumlins. In the area of the Lower Schussen basin (# 15 in Fig. 2) erosional scarps are substituted by moraines (for details, see Fig. 9).

4.2 Subglacial basins and related outwash plains

In the DTM we observe four km-sized plains outside the outer Würmian end moraine. The plains of Riedlingen, Federsee, Laupheim, and Wurzacher Ried (# 1, 2, 3, 4 in Fig. 2) show well preserved relics of braided stream deposits. Schreiner (1992b) and Ellwanger et al. (2011b) considered them late (Würmian) outwash plains resting on older (Rissian) subglacial basins fed from outlets initially starting at the northern tips of local lobes of the glacier producing the outer Würmian end moraine. Consequently, they rest upon older (Rissian

Fig. 3: South-western part of the Danubian meander plain upstream of Riedlingen (for position, see # 1 in Fig. 2). During initial ice retreat valley filling was dominated through braided outwash (1) from the Andelsbach (2), Ostrach (3), Wagenhauser Bach (4) and Schwarzach (5) valleys which today are only occupied by small rivulets. After ice retreat behind the drainage divide Danube/Rhine the Danube started to rework the northern part of the alluvium through randomly migrating point bars (6). The change in sedimentary regime is a result of the lower gradient and discharge of the Danube. Blue line: present course of the Danube; ERT: Ertingen; HER: Herbertingen; HOH: Hohentengen; MEN: Mengen; SCH: Scheer; Relic Drumlins: relics of drumlins from the previous (Riß) glaciation smoothed by multiple solifluction processes. Orthoview; illumination: 135/35; vertical exaggeration: x 10; pixel size: 8 m.

Abb. 3: Südwestlicher Teil der Schwemmebene der Donau (blau) flussaufwärts von Riedlingen (zur Lage siehe #1 in Abb. 2). Während des beginnenden Abschmelzprozesses dominierte ein verflochtenes Flusssystem (1), gespeist vom Andelsbach (2), der Ostrach (3), dem Wagenhauser Bach (4) und der Schwarzach (5), die heute nur noch kleine Bäche sind. Nachdem die Eisfront nach Süden hinter die Wasserscheide Donau/Rhein zurückwich, begann die Donau, den nördlichen Teil der Schwemmebene mit einem System von Mäanderschlingen umzugestalten (6). Der Wechsel im sedimentären Regime ist eine Folge des verminderten Gradienten und der geringeren Abflussmenge. ERT: Ertingen; HER: Herbertingen; HOH: Hohentengen; MEN: Mengen; SCH: Scheer; Relic Drumlins: Relikte von Drumlins aus der älteren Riß-Vergletscherung, die durch mehrfache Solifluktionsprozesse morphologisch degradiert sind. Orthoprojektion; Beleuchtung: 135/35; vertikale Überhöhung: x 10; Pixelgröße: 8 m.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or even older) outwash plain deposits which in turn already have been filling up ancient subglacial basins excavated as far North as Laupheim. Once Würmian ice had retreated behind the drainage divide Danube/Rhine runoff on outwash plains outside the outer Würmian end moraine (# 1, 2, 4 in Fig. 2) dwindled to the size of rivulets. In some basins, such as the Riedlingen basin (# 1 in Fig. 2), in the DTM it is possible to differentiate between remnants of the braided proglacial system and a Holocene meandering fluvial pattern (Fig. 3). As a consequence of its lower gradient the Danube reworked the northern part of the alluvium through randomly migrating point bars.

Inside the outer Würmian end moraine the DTM shows several radially oriented branch basins developed at different altitudes (# 5 to 12, 14 and 15 in Fig. 2). The branching arrangement of basins has been outlined by Ellwanger et al. (2011a, 2011b). Fig. 2 shows that these basins shallow towards the perimeter of glaciation; extension is slightly inferior to the plains located outside the outer Würmian end moraine. Just inside the outer Würmian end moraine of the Schussen lobe (label OWEM-SL in Fig. 2) a series of kilometre-sized elliptical troughs are the smallest basins found in the study area; details are shown in Figs. 4 and 5 (“x” marks). Outwash plains # 5, 6, 12, and 14 show undercutting of former slightly

Fig. 4: Ice wastage deposits produced between the outer and the inner Würmian end moraine during glacial retreat of the Schussen lobe of the Rhine glacier (areas 6, 7, 8 in Fig. 2). Description and numbering is from North to South and West to East.

Older (Rissian) drumlin fields overprinted by multiple solifluction processes*: (1).*

Outwash plains fed from breaches through the outer Würmian end moraine*: Saulgau plain (2), Riedtal plain (3), Haidgauer Heide (4).*

Schussen lobe of the outer Würmian end moraine*: white dotted line (OWEM-SL); strongly kettled in the western and northern sector, crested in the eastern sector. Inside the outer Würmian end moraine numerous kilometre-sized frontal basins can be clearly recognized (marked with “x”). For a view in higher resolution, compare Fig. 5.*

Fragmentary moraines inside the outer Würmian end moraine*: well defined in the northwestern sector (5a, 5b); low ridges of hummocks and kettles in the uppermost Schussen valley (6); replacement by terrain of chaotic ice decay landforms with irregular hummocks and kettle holes in the eastern sector (7). For more details, compare Fig. 5.*

Esker relics*: (8);* **possible kame terraces***: (9);* **possible relics of older (Rissian) drumlins***: (10).*

Channels parallel to the receding ice margin*: The Steinach valley probably originated as a channel parallel to the receding ice margin (upper course of the Steinach and prolongations as red and cyan dashed lines, respectively). After further ice retreat it changed into a braided stream flowing parallel to and migrating with the receding glacier (black and mauve dashed lines) shaping some scattered remains of hummocky moraines into streamlined relics. For a view in higher resolution, compare Fig. 5. The Durlesbach rivulet is a successor to the former Steinach stream. Initially it also drained towards the North firstly feeding the braided plains left by the disappearing Steinach stream (red and cyan dotted lines) then switching towards the main Schussen valley (black and mauve dotted lines).*

Inner Würmian end moraine*: white dotted line (IWEM); continuous ridge in the south-western sector, reduced to hummocks and kettles where it crosses the Schussen valley. Fragmentary moraines north of the inner Würmian end moraine are particularly well preserved around the Schreckensee lake area.*

Postglacial valley incision: *the steeply incised Schussentobel between Aulendorf and Mochenwangen became strongly overdeepened during glacial retreat towards the Föhrenried basin.*

Lettering (from North to South and West to East): BSch: Bad Schussenried, WIN: Winterstettenstadt, MUS: Musbach, HEB: Hebershaus, MIC: Michelwinnaden, AUL: Aulendorf, HOS: Hoßkirch, ALT: Altshausen, BWa: Bad Waldsee, PFR: Pfrunger Ried, SCH: Schreckensee lake, MOC: Mochenwangen, WIL: Wilhelmsdorf, BER: Bergatreute, FÖH: Föhrenried, WoAch: Wolfegger Ach.

Shaded grey areas: lakes. Inset: Position within Baden-Württemberg. Orthoview; illumination: 60/37; vertical exaggeration: x 6; pixel size: 16 m.

Abb. 4: Eiszerfallslandschaft zwischen der Äußeren und der Inneren Würmendmoräne (Gebiete 6, 7, 8 in Abb. 2). Die Beschreibung und Nummerierung geht von Nord nach Süd und West nach Ost.

Ältere (rißeiszeitliche) Drumlinfelder, überprägt von mehrfachen Solifluktionsprozessen*: (1).*

Schotterebenen, gespeist von Durchbrüchen durch die Äußere Würmendmoräne*: Saulgauer Ebene (2), Riedtal-Ebene (3), Haidgauer Heide (4).*

Schussen-Lobus der Äußeren Würmendmoräne*: weiße punktierte Linie (OWEM-SL), im westlichen und nördlichen Bereich mit vielen Toteislöchern, scharf konturiert im östlichen Bereich. Am Innenrand der Äußeren Würmendmoräne liegen zahlreiche kilometergroße Zungenbecken (mit „x“ markiert); Abb. 5 zeigt Details in höherer Auflösung.*

Diskontinuierliche Bögen von lokalen Moränenrücken innerhalb der Äußeren Würmendmoräne sind im nordwestlichen Bereich gut zu erkennen *(5a, 5b); im obersten Schussental erscheinen sie als reliktische, flache Rücken mit zahlreichen Toteislöchern (6). Im östlichen Bereich sind es eher chaotische Eiszerfallsformen mit unregelmäßigen Hügeln und Toteislöchern (7). Abb. 5 zeigt Details in höherer Auflösung.*

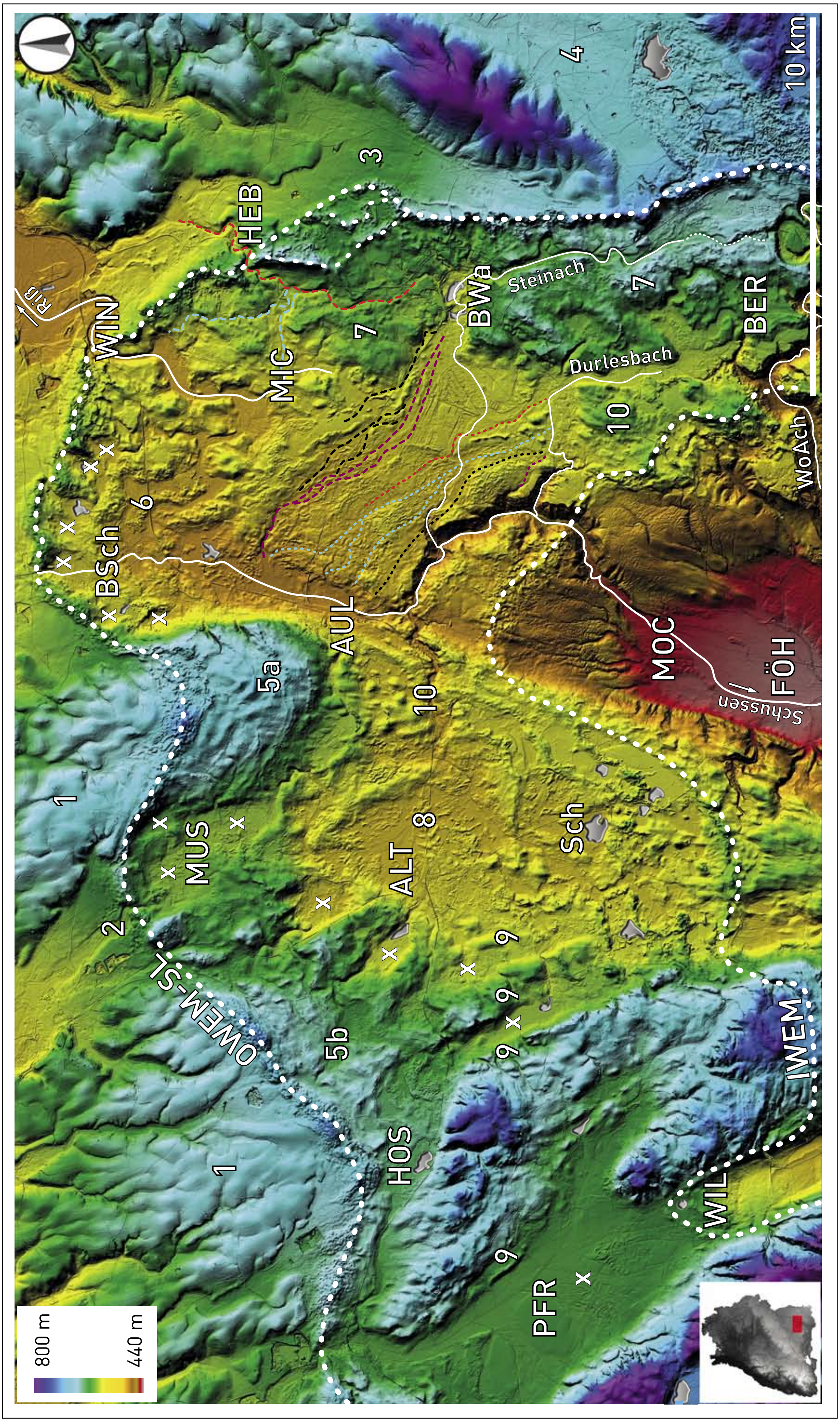
Eskerrelikte*: (8); mögliche Kameterrassen: (9); mögliche Relikte älterer (rißeiszeitlicher) Drumlins: (10).*

Eisrandparallele Rinnen*: Das Steinachtal entstand wahrscheinlich als eisrandparallele Rinne (Oberlauf der Steinach und seine ursprüngliche Fortsetzung nach Norden; rote und türkisfarbene gestrichelte Linien). Mit fortschreitendem Eiszerfall entwickelte sich ein verflochtenes Rinnensystem, das dem schwindenden Eisrand folgte (schwarze und violette gestrichelte Linien) und einige lokale Moränenrelikte stromlinienartig überformte. Abb. 5 zeigt Details in höherer Auflösung. Der Durlesbach ist ein Nachfolger des Steinach-Systems und entwässerte ursprünglich ebenfalls nach Norden, wo er zunächst die Zopfstrom-Ebene speiste, welche die Steinach hinterließ (rote und türkisfarbene punktierte Linien), bis er schließlich in Richtung Schussental umgelenkt wurde (schwarze und violette punktierte Linien).*

Innere Würmendmoräne*: weiße punktierte Linie (IWEM), als durchgehender Rücken im südwestlichen Bereich, reliktisch mit flachen Hügeln und Toteislöchern im Bereich des Schussentals. Diskontinuierliche Bögen von lokalen Moränenrücken nördlich der Inneren Würmendmoräne sind im Raum des Schreckensees gut erhalten.*

Postglaziale Flusseinschneidung*: die Übertiefung des Schussentobels zwischen Aulendorf und Mochenwangen begann nach dem Zurückweichen der Gletscherfront in das Föhrenried-Becken.*

Beschriftung von Nord nach Süd und West nach Ost: BSch: Bad Schussenried, WIN: Winterstettenstadt, MUS: Musbach, HEB: Hebershausen, MIC: Michelwinnaden, AUL: Aulendorf, HOS: Hoßkirch, ALT: Altshausen, BWa: Bad Waldsee, PFR: Pfrunger Ried, SCH: Schreckensee, MOC: Mochenwangen, WIL: Wilhelmsdorf, BER: Bergatreute, FÖH: Föhrenried, WoAch: Wolfegger Ach. Graue Flächen: Seen; Lage in Baden-Württemberg und Farbhöhencodierung: unten links; Orthoprojektion; Beleuchtung. 60/37; vertikale Überhöhung: x 6; Pixelgröße: 16 m.



800 m
440 m
10 km
Riß
WIN
HEB
MIC
BWa
Steinach
Durlesbach
BER
WoAch
BSch
AUL
MOC
FÖH
Schussen
5a
5b
MUS
ALT
Sch
OWEM-SL
HOS
IWEM
WIL
PFR

north-dipping gravel plains by reversely flowing post-glacial (latest Pleistocene to Holocene) Rhenish waters indicating that infill is related to backfill with outwash during consecutive stages of glacial retreat (Schreiner 1992b).

According to Preusser, Reitner & Schlüchter (2010) the main Lake Constance basin originated during the Last Glacial Maximum. In contrast, Ellwanger et al. (2011b) suggested that excavation of this basin is a late event produced by the glacier producing the inner Würmian end moraine.

4.3 Fragmentary, kettled and hummocky moraines

Ice wastage products such as fragmentary, kettled, or hummocky moraines (Dyke & Savelle 2000, Salcher, Hinsch & Wagreich 2010) are typical features of the broad belt between the outer and the inner Würmian end moraine (OWEM and IWEM in Fig. 2). In the sector of the Schussen lobe of the Rhine glacier (OWEM-SL in Fig. 2), especially in the shallow basins of the Aulendorf/Altshausen area (# 7 and 8 in Fig. 2), an extremely well-preserved population of almost all types of ice wastage geomorphology documents ice retreat in great detail (Figs. 4 and 5). Good preservation is a consequence of the position near the present-day Danube/Rhine drainage divide, largely preventing these features from erosional deterioration. In the western part of the Lake Constance region numerous suites of fragmentary moraines covering all stages of ice retreat have been mapped by Schreiner (1974, 1992a). In our entire study area fragmentary moraines are locally common, but not systematically recognizable throughout. The term kettled moraine has been introduced by Salcher, Hinsch & Wagreich (2010) to describe morphological features produced by dead ice particularly well detectable in a high-resolution DTM. Hummocky moraines are irregular landforms resulting from ablation of detrital load resting on the ice (Evans 2006, Munro-Stasiuk & Sjogren 2006). Most often, these accumulations are partly reworked by subglacial meltwater streams; laterally they might interfinger with eskers or kame terraces.

The outer Würmian end moraine (dotted line labelled OWEM-SL in Figs. 4 and 5) appears strongly kettled in the northern and north-western sector of Fig. 4, whereas it is sharply defined as a crested moraine in the eastern sector. Inside the outer Würmian end moraine a series of narrowly spaced (ca. 1 km) fragmentary recessional moraines can be traced parallel to the main ridge (Weidenbach 1975; # 5a, 5b in Fig. 4). On a larger scale (Fig. 5) up to six more or less concentric ridges can be identified. In places, these moraine fragments are reduced to low ridges of hummocks interspersed by kettles, in particular east and south-east of Bad Schussenried (# 6 in Fig. 4 and Fig. 5). In the eastern sector, the belt of recessional moraines is completely replaced by a terrain of chaotic ice decay landforms (# 7 in Fig. 4).

The inner Würmian end moraine (dotted line labelled IWEM in Fig. 4) forms an almost continuous ridge but appears reduced to hummocks and kettles where it crosses the Schussen valley. Fragmentary moraines north of the inner

Fig. 5: Detailed preservation of glaciogenic features in the area of the northernmost arc of the Schussen lobe of the Rhine glacier. Position corresponds to the north-eastern quadrant of Fig. 4. Colour scale has been adapted to highlight (in red colours) the large and complex flat area of the drainage divide between Danube (via the Riß river) und Rhine (via the Schussen river). SUS: Schussenursprung outlet, WIN: Winterstettenstadt breach, BSch: Bad Schussenried, HEB: Hebershaus breach, MIC: Michelwinnaden, AUL: Aulendorf.

Outer Würmian end moraine: *dotted red line (OWEM-SL), clearly defined despite strong overprint by kettles. On the inside it is accompanied by elliptical frontal branch basins (marked with "x") and a series of up to 6 fragmentary moraines (dashed white lines).*

Subglacial channels: *The uppermost course of the Schussen valley may have started to form as a subglacial channel draining the small Upper Schussen basin (grey colour) towards the Schussenursprung (SUS) or neighbouring outlets. In a similar way but on minor dimensions the uppermost part of the Riß valley between Winterstettenstadt and Michelwinnaden also may have originated as a subglacial feature.*

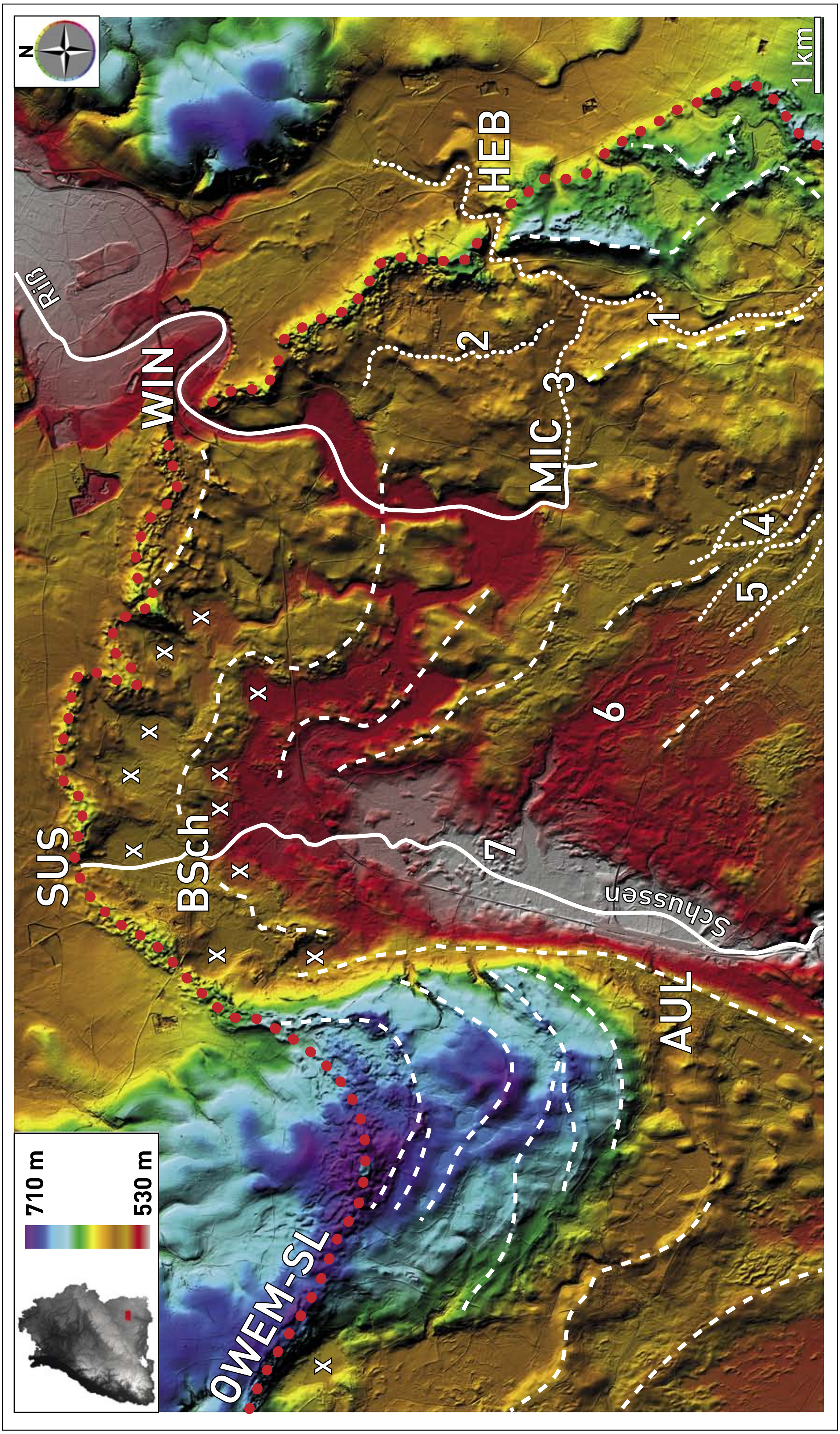
Channels parallel to the receding ice margin: *The Steinach valley (1, dotted white line; compare Fig. 4 for the wider geographic context) initially may have formed as a channel parallel to outer Würmian end moraine which it eventually crossed at the Hebershaus breach. With further ice retreat it became deflected towards the West (2, 3, white dotted lines) temporarily using the Winterstettenstadt breach. When the retreating glacier front reached the southern rim of the area shown the Steinach changed into a braided stream pattern flowing parallel to and migrating with the receding ice margin (4, 5, white dotted lines). On the outflow plain (6) strong stream flow reworked previous morphological features into streamlined relics; together with a field of chaotic hummocks further downstream (7) this suggests an origin by sudden release of floods caused by breaching of an ice-walled lake. Inset upper left: position within Baden-Württemberg and colour scale. Orthoview; illumination: 60/34; vertical exaggeration: x 5; pixel size: 8 m.*

Abb. 5: Detailgenaue Überlieferung eiszeitlicher Landschaftsformen im Bereich der Wasserscheide Donau/Rhein (nördlichster Schussen-Lobus des Rheingletschers). Die Lage entspricht dem nordöstlichen Quadranten auf Abb. 4. Die Farbhöhencodierung ist so angepasst, dass die weitläufige und komplexe Ebene im Bereich der Wasserscheide zwischen Donau (über die Riß) und Rhein (über die Schussen) in roten Farbtönen hervorgehoben ist. SUS: Schussenursprung-Durchbruch, WIN: Winterstettenstadt-Durchbruch, BSch: Bad Schussenried, HEB: Hebershausen-Durchbruch, MIC: Michelwinnaden, AUL: Aulendorf.

Äußere Würmendmoräne: *punktierte rote Linie (OWEM-SL), trotz zahlreicher Toteislöcher prägnant ausgebildet. Auf der Innenseite reihen sich zahlreiche kilometergroße elliptische Zungenbecken (mit „x" markiert) und mehrere diskontinuierliche Bögen von lokalen Moränenrücken (gestrichelte weiße Linien).*

Subglaziale Rinnen: *Der Oberlauf des Schussentals könnte als subglaziale Rinne entstanden sein und das obere Schussenbecken (grau) in Richtung auf den Schussenursprung (SUS) oder benachbarte Durchlässe entwässert haben. Als subglaziales Tal, aber in etwas kleinerer Dimension, könnte auch der Oberlauf des Rißtals zwischen Winterstettenstadt und Michelwinnaden begonnen haben.*

Eisrandparallele Rinnen: *Das Tal der Steinach (1, weiße punktierte Linie; zur Lage vgl. Abb. 4) ist möglicherweise als Rinne entstanden, die zunächst parallel zur Äußeren Würmendmoräne verlief und schließlich im Durchbruch von Hebershausen die Moräne kreuzte. Beim Zurückweichen der Eisfront wurde der Fluss nach Westen umgelenkt (2,3, weiße punktierte Linien), wobei er vorübergehend den Durchbruch von Winterstettenstadt benutzte. Als die Gletscherfront den südlichen Teil dieses Gebiets erreichte, breitete sich die Steinach als verflochtenes System in die angrenzende Ebene aus und verlagerte sich mit dem schwindenden Eisrand nach Süden (4,5, weiße punktierte Linien). In der Schwemmebene (6) wurden vorher existierende morphologische Strukturen zu stromlinienförmigen Relikten umgeformt. Zusammen mit einer Ansammlung chaotischer Hügel weiter flussabwärts (7) deutet das auf eine Entstehung durch Schichtfluten, wie sie beispielsweise beim Bersten von Eisrandstauseen auftreten. Lage in Baden-Württemberg und Farbhöhencodierung: oben links; Höhenfarbkodierung; Orthoprojektion; Beleuchtung 60/34; vertikale Überhöhung: x 5. Pixelgröße: 8 m.*


N
1 km
HEB
Riß
WIN
MIC
1
2
3
4
5
6
7
SUS
BSch
Schussen
AUL
OWEM-SL
710 m
530 m

Würmian end moraine are preserved in the Altshausen basin. In shallow depressions between these fragments of moraines peat bogs have been developing since ice retreat and some small lakes such as the Schreckensee persist until today.

4.4 Subglacial and ice-marginal meltwater channels

As a consequence of the position at the drainage divide between the Danube and the Rhine in the Aulendorf/Hebershausen/Bad Waldsee area (Figs. 4 and 5) an intricate pattern of channels parallel or perpendicular to the outer Würmian end moraine is preserved in great detail. The high-resolution DTM allows detailed morphometric analysis of these features resulting in a reconstruction of the glacio-fluvial history that elucidates the role of initial subglacial channels followed by complex sets of channels running parallel to the receding ice margin.

According to Benett & Glasser (2009) subglacial channels are oriented more or less perpendicularly to the ice margin and possess conspicuous convex-up or "humped" irregular long profiles interpreted as a consequence of their origin under pressurized flow. In the Alpine foreland Salcher, Hinsch & Wagreich (2010) described the main parameters of subglacial drainage valleys as follows: sinuous, convex-up long profiles, depths of up to 40 m, widths of up to 500 m, lengths in the order of kilometers; channels converge towards the outlet and there merge with proglacial outwash plains. In northern Germany the Weichselian glaciation produced subglacial valleys with dimensions that are an order of magnitude larger than in the Alpine foreland (Stackebrandt 2009).

The uppermost course of the Schussen river upstream of Aulendorf shallows and fades out towards the outer Würmian end moraine thus at least partly fulfilling the criteria for the recognition of subglacial valleys listed by Benett & Glasser (2009) and Salcher, Hinsch & Wagreich (2010). The Schussen river may have started to form as a subglacial valley excavated under pressurized flow draining the small Upper Schussen basin (Fig. 5). During the maximum extension of Würmian glaciation drainage should have crossed the Schussenursprung (SUS in Fig. 5) and neighbouring outlets feeding the adjacent Federsee outwash plain (# 2 in Fig. 2).

Channels parallel to the ice margin are described by Greenwood et al. (2007) and Benett & Glasser (2009) as systems that tend to form series of approximately straight stream beds parallel with contemporary contours and may possess sudden changes in direction. Inside the outer Würmian end moraine a complex set of channels parallel to the end moraine can be identified in the north-eastern quadrant of the area of Fig. 4.

In its upper course, the small Steinach valley follows the outline of the outer Würmian end moraine. In the DTM it becomes apparent that north of Bad Waldsee it initially drained northward (red dashed line in Figs. 4 and 5) suggesting an origin as a channel parallel to the receding ice margin outflowing through the Hebershaus breach in the outer Würmian end moraine. With ongoing ice retreat this channel became deflected towards the West (cyan dashed lines in Fig. 4; in Fig. 5 white dashed lines numbered 1, 2, and 3). When the retreating glacier eventually reached the area of Bad Waldsee, the Steinach predecessor changed into a braided stream flowing parallel to and migrating with the receding ice margin (black and mauve dashed lines in Fig. 4; in Fig. 5 white dashed lines numbered 4 and 5) reshaping some scattered remains of hummocky moraines into streamlined relics (# 6 in Fig. 5). In the field these features are almost impossible to identify as they occur in an area now mostly covered by dense vegetation (Tannwald forest). The reshaping of hummocks within a large field of interwoven strings of braided stream deposits evokes the effects of spontaneous flooding as a result from breaching ice-walled lakes. A good candidate would be the Bad Waldsee trough which until today harbours two small lakes (Fig. 4).

The Durlesbach valley north of Bergatreute also initially drained towards the North firstly feeding the braided plains left by the disappearing Steinach stream (red and cyan dotted lines in Fig. 4) then switching towards the main Schussen valley which gradually deepened as ice receded (black and mauve dotted lines in Fig. 4).

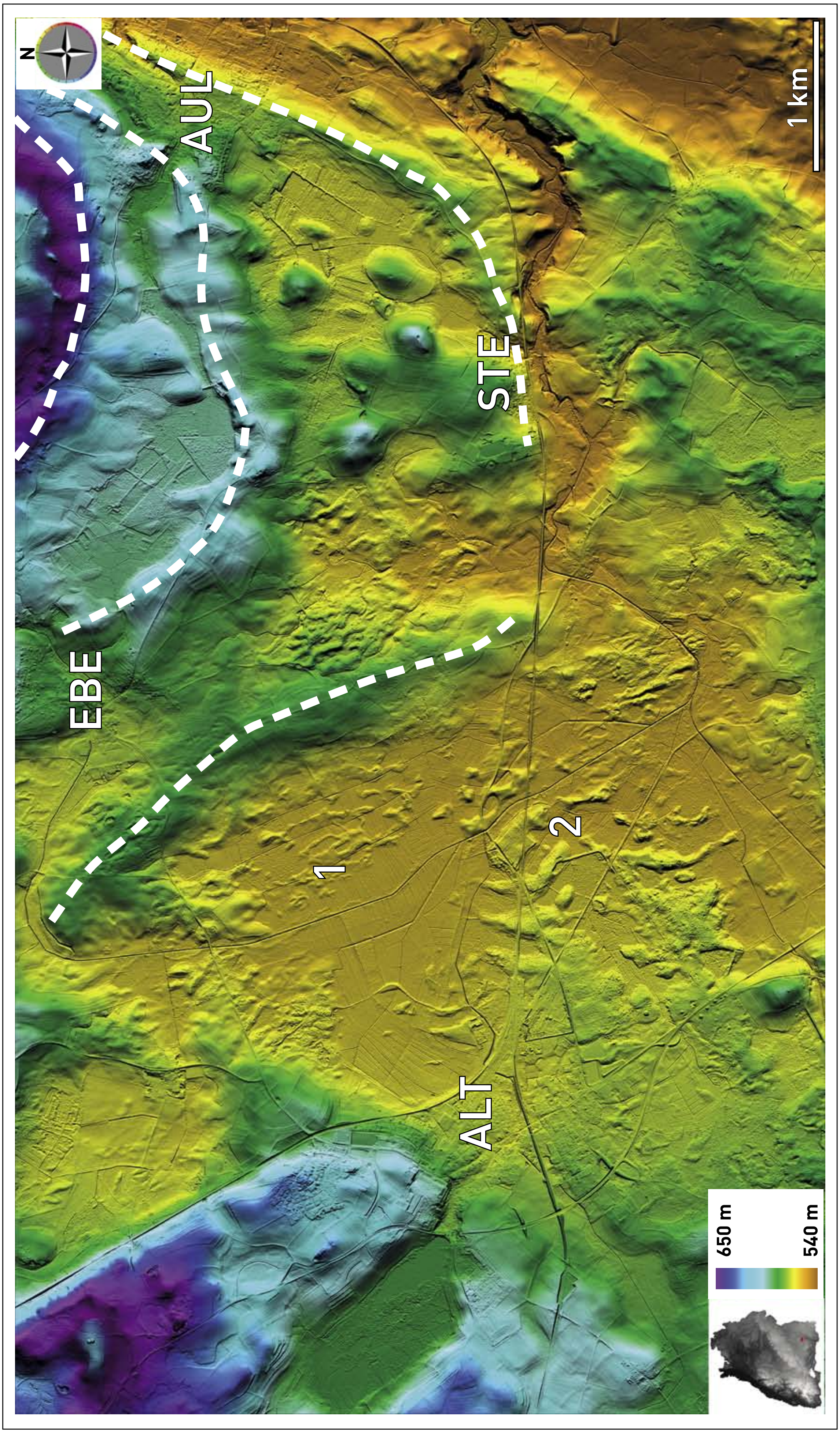
4.5 Esker relics and possible kame terraces preserved in the Altshausen plain

Within our study area eskers are rarely observed. Best preservation again is given near the drainage divide Danube/Rhine, especially in the Altshausen plain (Figs. 2, 4 and 6). According to Gripp (1978), Strehl (1998), Grube (2011) and Benett & Glasser (2009) eskers are sinuous subglacial ridges which may occur singly or in a braided pattern. Braided eskers are often associated with kame terraces, kettled topography and hummocky moraines (Evans 2006, Benett & Glasser 2009). According to Salcher et al. (2009) and Benett & Glasser (2009) kame terraces develop synchronously to ice wastage along the flanks of ice lobes. Common marks are the diamictitic rock texture and occasional Gilbert-type deltas of varying dimensions; they may occur singly or in parallel flights of terraces with heights of up to tens of meters.

The Altshausen plain appears to be a composite of several rather small branch basins filled with basal till as well as fragmentary and hummocky moraines (Fig. 6; for a view of the wider geographic context, compare Figs. 4 and 2). Conspicuous morphological features are elongated, up to 800 m long ridges standing between 1 and 5 m above the level of the surrounding basal till. Due to their low relief and the vegetation cover they are hard to recognize in the field and

Fig. 6: Esker relics preserved in the Altshausen plain. Eskers range in height from 1 m (1) to 5 m (2) and are up to 800 m long. Dashed white lines: fragmentary recessional moraines inside the outer Würmian end moraine. EBE: Ebersbach, AUL: Aulendorf, ALT: Altshausen, STE: Steinenbach. Inset lower left: position within Baden-Württemberg and colour scale. Orthoview; illumination: 90/35; vertical exaggeration: x 4; pixel size: 4 m.

Abb. 6: Relikte von Eskern in der Altshausener Ebene. Die Esker sind zwischen 1 m (1) und 5 m (2) hoch und bis 800 m lang. Gestrichelte weiße Linien: diskontinuierliche Bögen von lokalen Moränenrücken innerhalb der Äußeren Würmendmoräne. EBE: Ebersbach, AUL: Aulendorf, ALT: Altshausen, STE: Steinbach. Lage in Baden-Württemberg und Farbhöhencodierung: unten links; Orthoprojektion; Beleuchtung: 90/35; vertikale Überhöhung: x 4; Pixelgröße: 4 m.


N
AUL
STE
EBE
ALT
1
2
1 km
650 m
540 m

not mapped on scale 1:25000 (Weidenbach 1975) but are well recognizable in a vertically exaggerated DTM (# 8 in Fig. 4, # 1 and 2 in Fig. 6) and interpreted as eskers. Cross-sections are exposed along the railway line directly east of Altshausen station. The DTM also reveals markedly elongated ridges (# 9 in Fig. 4) partly bordering kilometre-sized branch basins ("x" in Fig. 4). Despite the lack of diagnostic field criteria such as delta deposits we tentatively interpret these structures as possible kame terraces.

4.6 Micromoraines preserved in the Röschenwald forest

About 6 km south of Aulendorf string-like, more or less parallel ridges with heights only between 1 and 2 m and maximum lengths of 200 m are exquisitely preserved within a densely forested area named Röschenwald (approximately 20 to 30 km²) extending on both sides of the lower part of the Schussentobel (Fig. 7; compare Figs. 4 and 2 for the local context). In a densely forested area these structures would escape the attention of even an experienced geologist. However, after knowing from the DTM what to look for they can be recognized indeed, albeit only when following a tight search pattern ignoring obstacles. As far as we could realize during our ground checks these ridges probably consist of material comparable to reworked basal till although as a consequence from extremely poor outcrop conditions diagnostic criteria such as diamictitic till texture and striated boulders cannot be ascertained at the moment. These features are superimposed to the upper slope of the Föhrenried basin North of Ravensburg (# 14 in Fig. 2, compare also Fig. 4) forming a slightly inclined ramp dipping from 575 to 550 m over a distance of 5 km (gradient: 5 ‰). In the lower part of the slope (transition from brown to red colours in Fig. 7) these features gradually disappear being replaced by smooth basal till surfaces.

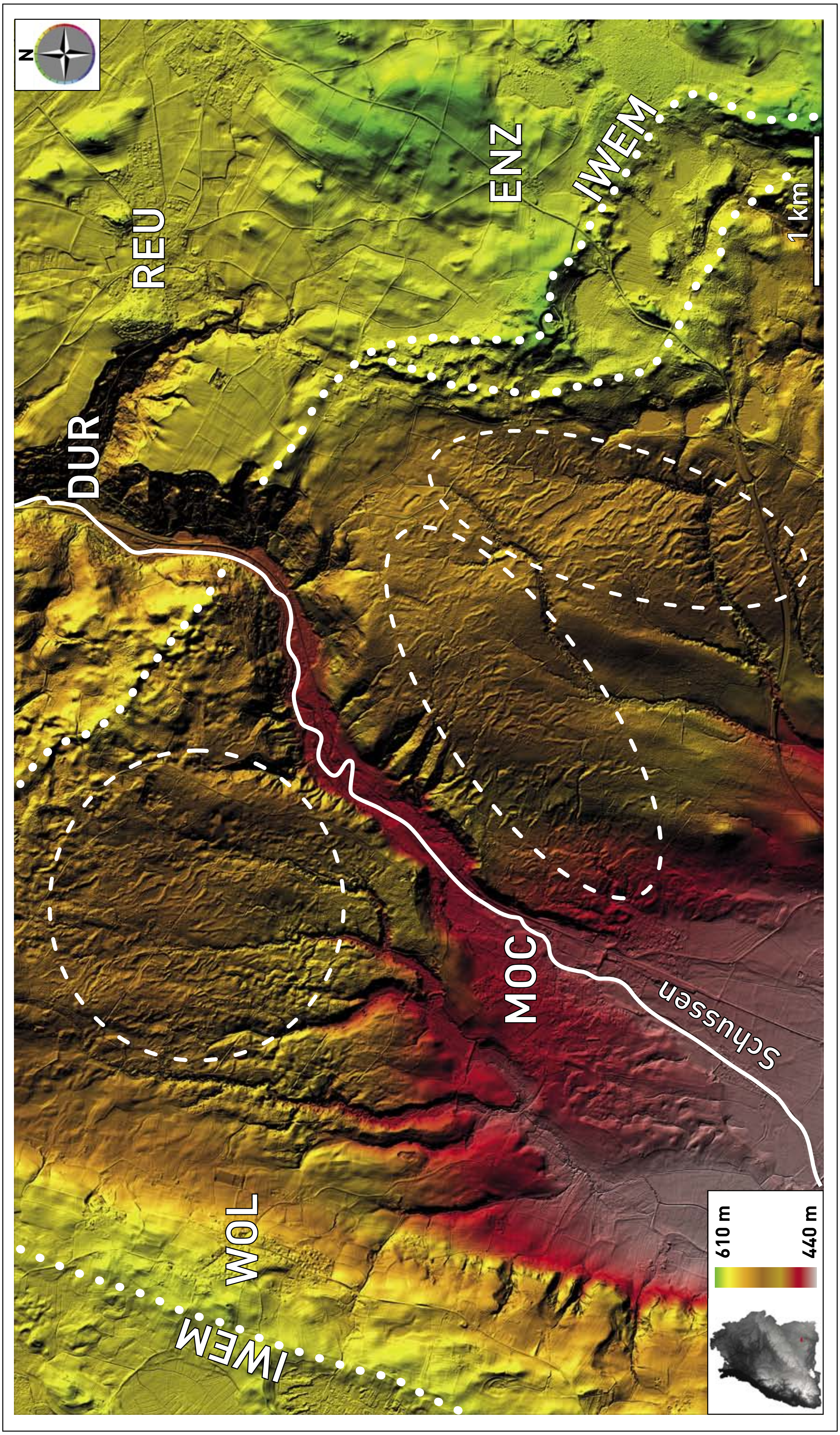
String-like moraines commonly are regarded products of intermittent episodes of backmelting and readvance of the glacier front (Schreiner 1992b). Based on actualistic observations in Spitsbergen, however, Stackebrandt et al. (1997) pointed out that there are two alternatives to the common model of oscillatory movement of ice: a) push moraines and b) supraglacial moraines. *Push moraines* result from folding, imbrication and/or thrusting of proglacial material related to local surges during stationary episodes. Commonly they form concentric garland-like structures surrounding the snout of glaciers. From the petrographic point of view the decisive criterion for recognition is well-visible soft-sediment deformation affecting proglacial sediments only; subglacial material such as basal till and striated boulders is only marginally involved. A well-known example from northern Germany is the Muskauer Faltenbogen (Kupetz 1996). However, the dimensions of such push moraines are an order of magnitude larger than the patterns observed.

Following Stackebrandt et al. (1997) and Hättestrand & Johansen (2005) *supraglacial moraines* commonly are metre-thick ridges covering blue ice. They mainly result from transport of subglacial material along shear bands in areas of compressive ice flow (i.e., grounded glacier snouts); folding can occur locally and larger moraines may be pitted with sink holes. At the surface this debris accumulates as meltout till or sublimation till. Supraglacially entrained colluvium from surrounding slopes might be an additional source of material (Hättestrand & Johansen 2005); petrographic distinction from push moraines is based on the dominance of angular clasts and the presence of diamictitic till texture and striated boulders. Dimensions and spacing of the ridges at the Röschenwald site might be in accordance with an interpretation as supraglacial moraines. These features do not occur elsewhere in the entire study area. The Röschenwald site is exceptional inasmuch as it is the only region forming an extended, slightly inclined ramp facing the ancient retreating glacier front. The observed ridges are distinctly smaller than continuous or fragmentary moraines and follow a much more regular pattern than hummocky moraines. Due to the extremely poor outcrop conditions, however, a supraglacial origin resulting from shearing in frontal parts of the glacier accompanied by entrainment of basal till cannot be confirmed so far. Therefore, we rather prefer the descriptive term *micromoraines* for the string-like ridges in the Röschenwald site, reaching heights between 1 and 2 m and maximum lengths of 200 m.

In the DTM, on the other hand, it is obvious that at the time of the formation of the mircromoraines the glacier snout was facing the slightly south-dipping upper rim of the Föhrenried basin. Increased basal shear stress might indeed have resulted in extensive frontal shearing and overthrusting producing supraglacial meltout/sublimation moraines. Their gradual disappearance upon the lower part of the ramp might be interpreted as the consequence of accelerated ice retreat.

Fig. 7: Micromoraines (circled areas) on the forest-covered northern slope of the Föhrenried basin; the region corresponds to the south-central part of Fig. 4. The brown-coloured surfaces display a dense (roughly hundred-metre-spaced) succession of micromoraines with heights between 1 and 2 m and lenghts in the order of 100 m interpreted to reflect valley glacier retreat upon the slightly inclined upper ramp of the Föhrenried basin. The deeply incised lower part of the Schussentobel between Durlesbach and Mochenwangen is a product of post-glacial erosion towards the base level of the Föhrenried basin. Dotted white line: inner Würmian end moraine (IWEM). DUR: Durlesbach, REU: Reute, WOL: Wolpertswende, ENZ: Enzisreute, MOC: Mochenwangen. Inset lower left: position within Baden-Württemberg and colour scale. Orthoview; illumination: 60/34; vertical exaggeration: x 5; pixel size: 4 m.

Abb. 7: Mikromoränen (eingekreiste Gebiete) auf der waldbedeckten nördlichen Böschung des Föhrenried-Beckens; das Gebiet entspricht dem mittleren südlichen Sektor von Abb. 4. Die bräunlichen Teile der Oberfläche zeigen eine dichte Abfolge von Mikromoränen (1 bis 2 m hoch, 100–200 m lang, Abstände im Bereich 100 m), die während des Rückschmelzens des Talgletschers auf der leicht nach Süden geneigten oberen Böschung des Föhrenried-Beckens entstanden sein müssen. Der tief eingeschnittene Schussentobel ist das Ergebnis postglazialer rückschreitender Erosion auf das Niveau des Föhrenried-Beckenbodens. Punktierte weiße Linie: Innere Würmendmoräne (IWEM). DUR: Durlesbach, REU: Reute, WOL: Wolpertswende, ENZ: Enzisreute, MOC: Mochenwangen. Lage in Baden-Württemberg und Farbhöhencodierung: unten links; Orthoprojektion; Beleuchtung: 60/34; vertikale Überhöhung: x 5; Pixelgröße: 4 m.


N
REU
ENZ
IWEM
1 km
DUR
MOC
Schussen
WOL
IWEM
610 m
440 m

4.7 Complex landforms at the Binzen bifurcation of the outer Würmian end moraine

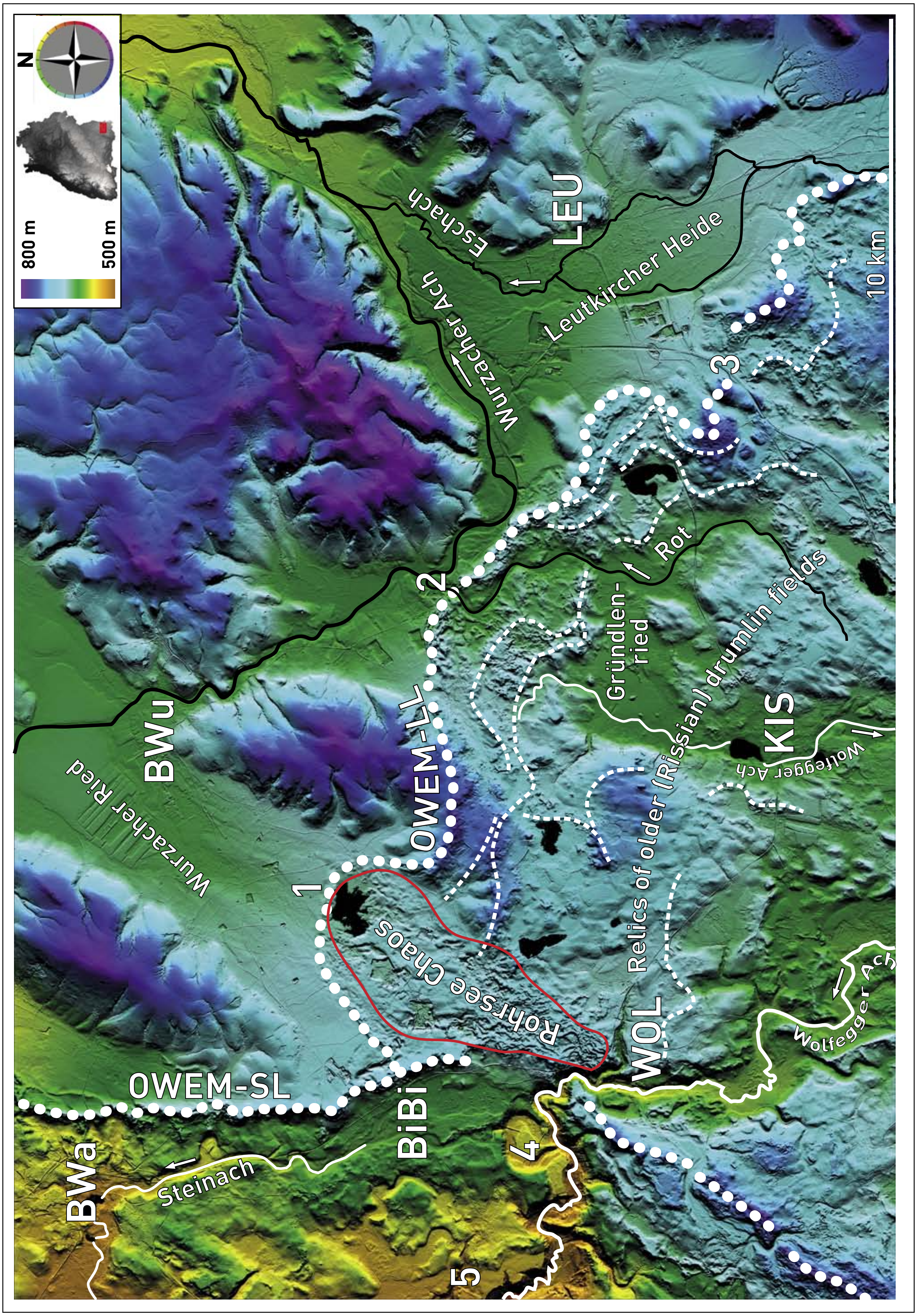
The region covered by Fig. 8 shows a remarkable example for complex pattern of intricately interwoven glacial landforms. The outer Würmian end moraine bifurcates at the hamlet of Binzen (BiBi in Figs. 2 and 8). Both branches of outer Würmian end moraines are clearly outlined. At the scale shown in Fig. 8 it becomes evident that the end moraine of the Schussen lobe (OWEM-SL) markedly crosscuts the adjacent end moraine of the Leutkirch lobe (OWEM-LL), indicating that the Schussen lobe had persisted longer than the Leutkirch lobe. This fact provides valuable arguments for the reconstruction of the glacial and post-glacial history of the area. Inside the Leutkirch lobe up to four fragmentary recessional moraines are locally well defined (dashed lines in Fig. 8), which is also known from geologic mapping at a scale of 1:25000 (Szenkler & Ellwanger 1995, Szenkler & Ellwanger 1997).

Outflow from the Leutkirch lobe must have been strong because all surrounding ancient Rissian subglacial basins (Wurzacher Ried and Leutkircher Heide) are filled almost to the level of the Würmian end moraine. Main breaches were situated in the Rohrsee area and at Hünlishofen and Bettelhofen (# 1, 2, 3 in Fig. 8). A considerable part of the sediment supply to the Leutkircher Heide plain also came from the broad South-North-oriented Eschach valley paralleling the former ice margin.

Today the drainage divide between Danube and Rhine crosses the Gründlenried plain. This plain most probably

Fig. 8: Complex landforms at the Binzen bifurcation (BiBi) of the outer Würmian end moraine. Black lines: Danubian rivers; white lines: Rhenish rivers. Black patches: lakes. Lettering from North to South and West to East: BWa: Bad Waldsee, BWu: Bad Wurzach, LEU: Leutkirch, WOL: Wolfegg, KIS: Kißlegg.
Outer Würmian end moraines *(dotted white lines): End moraine of the Schussen lobe of the Rhine glacier: OWEM-SL; end moraine of the Leutkirch lobe of the Rhine glacier: OWEM-LL. Note that the end moraine of the Schussen lobe (OWEM-SL) crosscuts the end moraine of the Leutkirch lobe (OWEM-LL) meaning that the Schussen lobe had persisted longer than the Leutkirch lobe. Major breaches in the Leutkirch lobe end moraine: Rohrsee (1), Hünlishofen (2), Bettelhofen (3). Fragmentary moraines inside the Leutkirch lobe: dashed white lines.*
Fan of strongly reworked ice decay deposits: *Rohrsee Chaos (red-rimmed area); this fan is interpreted as a result of spontaneous flooding from the breaching of an ice-walled lake. As a consequence from subsequent incision of the Wolfegger Ach valley the apex of the fan and parts of the original feeding area are no longer preserved.*
Subglacial channels: *The uppermost course of the Wolfegger Ach in the Kißlegg area shows characteristics for an interpretation as a subglacial channel. Initially it should have drained reversely (northward) joining the lower Rot valley across the Gründlenried plain and eventually breaching the outer end moraine at the Hünlishofen outlet (2). At a higher level than today (cyan colours) the lower course of the Wolfegger Ach upstream of Wolfegg also may have started as a subglacial valley feeding the Wurzacher Ried plain. The last product of this high-level drainage system would have been the Rohrsee Chaos.*
Channel parallel to the receding OWEM-SL ice margin: *After its initial subglacial valley stage the Wolfegger Ach upstream of Wolfegg started to incise breaching the Schussen lobe end moraine (OWEM-SL) following the south-westerly receding ice margin creating a first channel which is the valley today occupied by the Steinach (compare Fig. 4 for the prolongation towards the North). Further incision of the Wolfegger Ach resulted in the formation and subsequent undercutting of the valley meander of Witschwende (4). Laterally this level corresponds to the early Durlesbach system (5) developing as a late channel parallel to the vanishing ice margin (compare Fig. 4 for the prolongation towards the North).*
Relics of drumlins: *In the Kißlegg sector a large fan of drumlins can be recognized, but in comparison with the pristine examples presented in Fig. 9 these drumlins appear rather deteriorated. We conclude that these features are relics of older Rissian drumlin fields that largely escaped Würmian glacial erosion as a result from reduced shear stress under a relatively thin ice sheet. Inset upper right: colour scale and position within Baden-Württemberg. Orthoview; illumination: 90/35; vertical exaggeration: x 4; pixel size: 16 m.*

Abb. 8: Komplexe eiszeitliche Landschaftsformen im Bereich der Bifurkation von Binzen (BiBi, Äußere Würmendmoräne). Schwarze Linien: Donauzuflüsse; weiße Linien: Rheinzuflüsse. Schwarze Flächen: Seen. Beschriftung von Nord nach Süd und West nach Ost: BWa: Bad Waldsee, BWu: Bad Wurzach, LEU: Leutkich, WOL: Wolfegg, KIS: Kißlegg.
***Äußere Würmendmoränen** (punktierte weiße Linien): Endmoräne vom Schussen-Lobus des Rheingletschers (OWEM-SL); Endmoräne vom Leutkirch-Lobus des Rheingletschers (OWEM-LL). Größere Durchbrüche durch die Endmoräne des Leutkirch-Lobus: Rohrsee-Pforte (1), Hünlishofen (2), Bettelhofen (3). Diskontinuierliche Bögen von lokalen Moränenrücken innerhalb des Leutkirch-Lobus: weiße gestrichelte Linien.*
***Rohrsee-Chaos** (rote Umrandung): ein Fächer aus aufgearbeiteten Eiszerfallsablagerungen, interpretiert als Ergebnis einer Schichtflut aus einem berstenden Eisrandstausee. Der Apex des Fächers und Teile des Zustromgebiets sind durch die postglaziale Übertiefung des Tals der Wolfegger Ach nicht mehr erhalten.*
***Subglaziale Rinnen**: Im Raum Kißlegg zeigt der Oberlauf der Wolfegger Ach morphometrische Merkmale, die auf eine Entstehung als subglaziale Rinne deuten. Demnach hätte dieser Raum ursprünglich nach Norden entwässert und über die Ebene von Gründlenriet und das untere Rottal den Durchbruch von Hünlishofen (2) erreicht. Ebenso wahrscheinlich ist es, dass auch der Unterlauf der Wolfegger Ach stromauf von Wolfegg auf einem höheren Niveau als heute (Farbton: türkis) als subglaziale Rinne begonnen hat und in die Ebene des Wurzacher Rieds entwässerte. Der jüngste und letzte Zeuge dieses relativ hochliegenden Drainagesystems dürfte das Rohrsee-Chaos sein.*
***Eisrandparallele Rinnen**: Mit dem Zurückweichen des Schussen-Lobus begann die Wolfegger Ach, sich einzutiefen und durchbrach zunächst die Endmoräne nördlich von Wolfegg. Als erste eisrandparallele Rinne entwickelte sich dann das Tal, das heute in Teilen noch vom Oberlauf der Steinach eingenommen wird (vgl. Abb. 4 für die Fortsetzung nach Norden). Mit fortschreitender Eintiefung wurde die Steinach-Rinne deaktiviert und es entstand die Talschlinge von Witschwende (4). Auch diese wurde durch ein weiteres kurzlebiges System unterschnitten, welches auf das Niveau des frühen Durlesbachs (5) ausgerichtet war (vgl. Abb. 4 für die Fortsetzung nach Norden).*
***Drumlin-Relikte**: Im Raum Kißlegg ist ein großer Fächer von Drumlins zu erkennen, doch im Gegensatz zu den detailgenau erhaltenen Vorkommen von Abb. 9 sind diese Drumlins morphologisch degradiert. Wir halten die Strukturen für Relikte rißeiszeitlicher Drumlinfelder, die wegen der geringen Mächtigkeit des Leutkirch-Lobus während der Würmvereisung nur teilweise erodiert wurden.*
Lage in Baden-Württemberg und Farbhöhencodierung: oben rechts; Orthoprojektion; Beleuchtung: 90/35; vertikale Überhöhung: x 4; Pixelgröße 16 m.



N
800 m
500 m
LEU
Eschach
Leutkircher Heide
Wurzacher Ach
10 km
3
2
Rot
Gründlen-
ried
Relics of older (Rissian) drumlin fields
KIS
Wolfegger Ach
BWu
Wurzacher Ried
OWEM-LL
1
Rohrsee Chaos
WOL
OWEM-SL
BiBi
4
5
BWa
Steinach

results from the filling of a small and shallow subglacial basin. It seems very probable that the uppermost course of the Wolfegger Ach originated as a subglacial valley initially draining reversely, crossed the Gründlenried area, joined the lower Rot valley, and breached the outer end moraine at Hünlishofen. At a much higher level than today (cyan colours in Fig. 8) the Wolfegger Ach upstream of Wolfegg most probably also started as a subglacial valley draining upon the outwash plain of the Wurzacher Ried. After ice retreat of the Leutkirch lobe to a line south of Wolfegg, the Schussen lobe must have persisted, deflecting the entire meltwater outflow of the Leutkirch lobe towards the Wurzacher Ried plain. From the occurrence of a fan-shaped field of chaotic deposits (named Rohrsee Chaos in Fig. 8) we conclude that an ice-walled lake must have existed temporarily in this area. The release of a large flood by breaching would explain the existence of this extraordinary morphological feature. Recently, and also on the basis of DEM analysis similar phenomena have been discovered in north-western Germany (Winsemann et al. 2011). In the field, however, it is hardly possible to identify any of the particular marks clearly visible in the DTM.

When the Schussen lobe eventually also started to melt back the Wolfegger Ach breached the Schussen lobe end moraine creating at first a channel running parallel to the receding ice margin which is the valley today occupied by the Steinach running towards Bad Waldsee (Fig. 8; compare Fig. 4 for its prolongation towards the North). With ongoing ice retreat the Steinach system became replaced by the Durlesbach system developing at a lower level and slightly further West as a late channel parallel to the vanishing ice margin (Fig. 4 and # 5 in Fig. 8).

4.8 Drumlins

Würmian drumlins

In the study area, on geological maps at a scale of 1:25000 (Schmidt & Bräuhäuser 1913, Bräuhäuser 1976, Schmidt & Münst 1978, Schreiner 1978, Erb 1989, 1995, Szenkler & Ellwanger 1995, Schmidt 1998, Jaud, Szenkler & Ellwanger 2001) drumlins are identified with great accuracy. Length/width/height ratios have been noted accordingly but a clear distinction into separate fields of high- and low-convexity drumlins has not been made so far. In the DTM the area between the inner Würmian end moraine and the last stationary (mainly erosional) episode during glacial retreat ("Konstanzer Stadium", label "KS" in Figs. 2 and 9) is a textbook example of the radial arrangement and lateral morphological variability of Würmian drumlins produced under a thick ice load during maximum extension of the glacier. Fig. 9 shows this fan-shaped arrangement of drumlins in the Überlingen - Friedrichshafen - Ravensburg triangle.

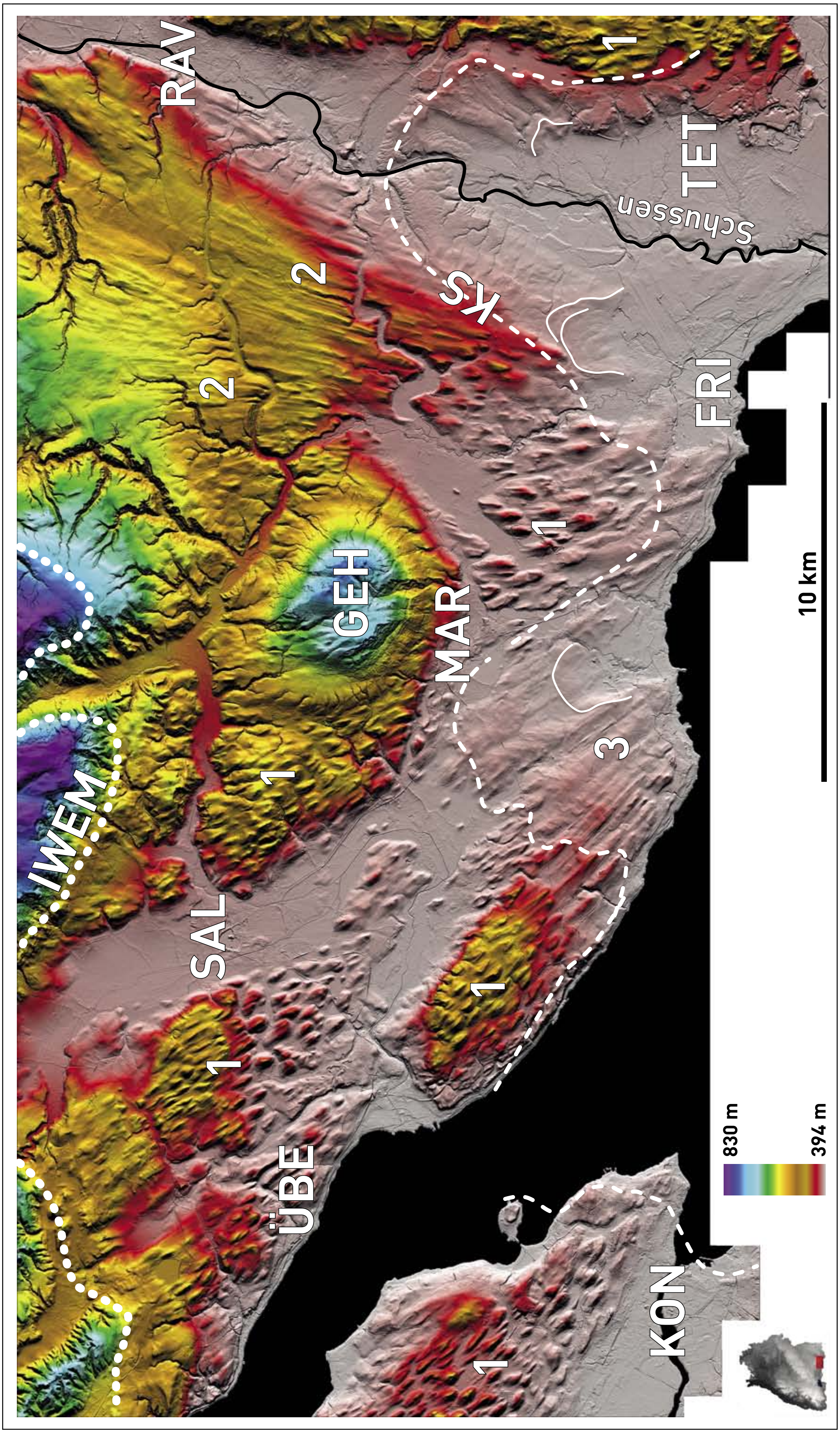
Within this domain, radially elongated high-convexity drumlins (Clark et al. 2009: "classically-shaped drumlins") distally grade into low-convexity equivalents (Clark et al. 2009: "spindle-shaped drumlins") fading out with distance (for an overview in regional context, compare Figs. 1 and 2). In the DTM high-convexity drumlins (# 1 in Fig. 9) are more or less elliptical in map view, possess lengths of up to 1 km, maximum heights of 60 m and often show a marked crest line. Low-convexity drumlins (# 2 in Fig. 9) are extremely elongated, streamlined hills with maximum lengths of 4 km and maximum heights of 20 m although the average elevation above the surrounding basal till surface is only around 5 m.

In the DTM (Figs. 1, 2, and 9) it appears that high-convexity drumlins are the common case in the region, whereas low-convexity drumlins are restricted to the western flank of the lower Schussen valley and an area south of Markdorf. Schmidt (1998) suggested that the shape of such hills depends on the gradient of the surface underneath the ice sheet. We observe that high-convexity drumlins occur where the local gradient is steeper and low-convexity drumlins occur where a broad ramp with a very low gradient exists, especially along the western side of the Lower Schussen basin. An obvious explanation would be that as a consequence from the low gradient ice flow rates were high enough to allow basal till material to be thoroughly smeared out rather than shaped into the classical sheep-back styled hills. In contrast, a slower ice motion on steeper ground would reduce shear stress at the base of the ice sheet resulting in drumlins of higher convexity.

It might be speculated whether the flat ramp that bears the low-convexity drumlins is an inheritance from Rissian times, e.g., a relic of the floor of a formerly much wider subglacial basin (predecessor of the Würmian Lower Schussen

Fig. 9: Drumlins in the Lake Constance (black) area. Black line: lower Schussen river; white dotted line: inner Würmian end moraine (IWEM); white dashed line: "Konstanzer Stadium" line (KS); thin white lines: fragmentary moraines inside the KS line. Lettering from North to South and West to East: RAV: Ravensburg, SAL: Salem, ÜBE: Überlingen, GEH: Gehrenberg, MAR: Markdorf, KON: Konstanz, FRI: Friedrichshafen, TET: Tettnang.
Drumlins occur in the segment between the inner Würmian end moraine (IWEM) and the "Konstanzer Stadium" line (KS) forming a radially fanning belt. High-convexity drumlins (1) are abundant in the western part of this region. Low-convexity drumlins (2) are restricted to the western side of the Lower Schussen valley. Inside the "Konstanzer Stadium" line drumlins appear truncated (3) as a result from erosion underneath a shallow ice sheet during this last stationary episode. Inset lower left: position within Baden-Württemberg and colour scale. Orthoview; illumination: 90/38; vertical exaggeration: x 4; pixel size: 16 m.

Abb. 9: Drumlins im Gebiet des Bodensees (schwarz). Schwarze Linie: Schussen; weiße punktierte Linie: Innere Würmendmoräne (IWEM); weiß gestrichelt: Ausstrich von Endmoräne und lokalen kliffähnlichen Abschürfungsmerkmalen des „Konstanzer Stadiums" (KS); dünne weiße Linien: Moränenrelikte innerhalb der Endmoräne des Konstanzer Stadiums. Beschriftung von Nord nach Süd und West nach Ost: RAV: Ravensburg, SAL: Salem, ÜBE: Überlingen, GEH: Gehrenberg, MAR: Markdorf, KON: Konstanz, FRI: Friedrichshafen, TET: Tettnang.
Würmeiszeitliche Drumlins kommen vorwiegend im Segment zwischen der Inneren Würmendmoraine (IWEM) und der Endmoräne des „Konstanzer Stadiums" (KS) vor und bilden dort einen radial aufgefächerten Gürtel. Hochkonvexe Drumlins (1) dominieren im Westen, niedrigkonvexe Drumlins (2) sind auf die Westflanke des unteren Schussentals beschränkt. Innerhalb der Endmoräne des „Konstanzer Stadiums" (KS) besitzen die Drumlins ein Aussehen, das auf Abschliff durch eine dünne Eisdecke deutet. Lage in Baden-Württemberg und Farbhöhencodierung: unten links; Orthoprojektion; Beleuchtung: 90/38; vertikale Überhöhung: x 4; Pixelgröße 16 m.


RAV
TET
Schussen
KS
FRI
2
2
GEH
MAR
1
1
3
10 km
IWEM
SAL
1
1
ÜBE
830 m
394 m
KON
1
1

basin). In literature (Schmidt & Münst 1978, Schreiner 1978, Erb 1995, Schmidt 1998) there has also been some discussion on the question whether the drumlins themselves should be considered a Rissian inheritance. The pristine preservation clearly visible in the DTM, however, suggests that these drumlin fields are authentic Würmian phenomena. It also indicates that ice retreat between the inner Würmian end moraine and the KS line must have been so rapid as to leave the drumlins mostly unharmed by overprinting through processes of prolonged ice wastage.

Inside the "Konstanzer Stadium" (KS) line drumlins appear strongly flattened (# 3 in Fig. 9) and generally provide an abraded appearance. In our opinion this truncation could have occurred under a temporary shallow ice cover during this last stationary episode in ice retreat. A few fragments of moraines (white lines in Fig. 9) presumably are the youngest glacial features preserved in south-western Germany. There has been some debate as to whether a "Konstanzer Stadium" (Schreiner 1974, 1992a, Keller & Krayss 1994, 2000, Geyer, Schober & Geyer 2003) did exist at all (Ellwanger et al. 2011b). From the evidence provided by the DTM, however, there is no doubt that a stationary episode occurred indeed producing abrasional phenomena in the western part of the area of Fig. 9 and moraines in the Lower Schussen valley.

Rissian drumlins

Würmian drumlins are typically restricted to the area inside the inner Würmian end moraine (see Fig. 2). Outside (north of) the outer Würmian end moraine morphology is dominated by gentle undulating hills most probably representing older (Rissian) drumlin fields overprinted by multiple solifluction processes (# 1 in Fig. 4, Schmidt & Münst 1978, Schreiner 1978, Erb 1995, Schmidt 1998).

In the space between the outer and inner Würmian end moraine the DTM reveals some probable relics of Rissian drumlins (# 10 in Fig. 4). In our opinion, an occurrence of drumlin-like structures within the belt between the outer and the inner Würmian end moraines rather points to an origin as older (Rissian) drumlins which in places escaped Würmian glacial abrasion.

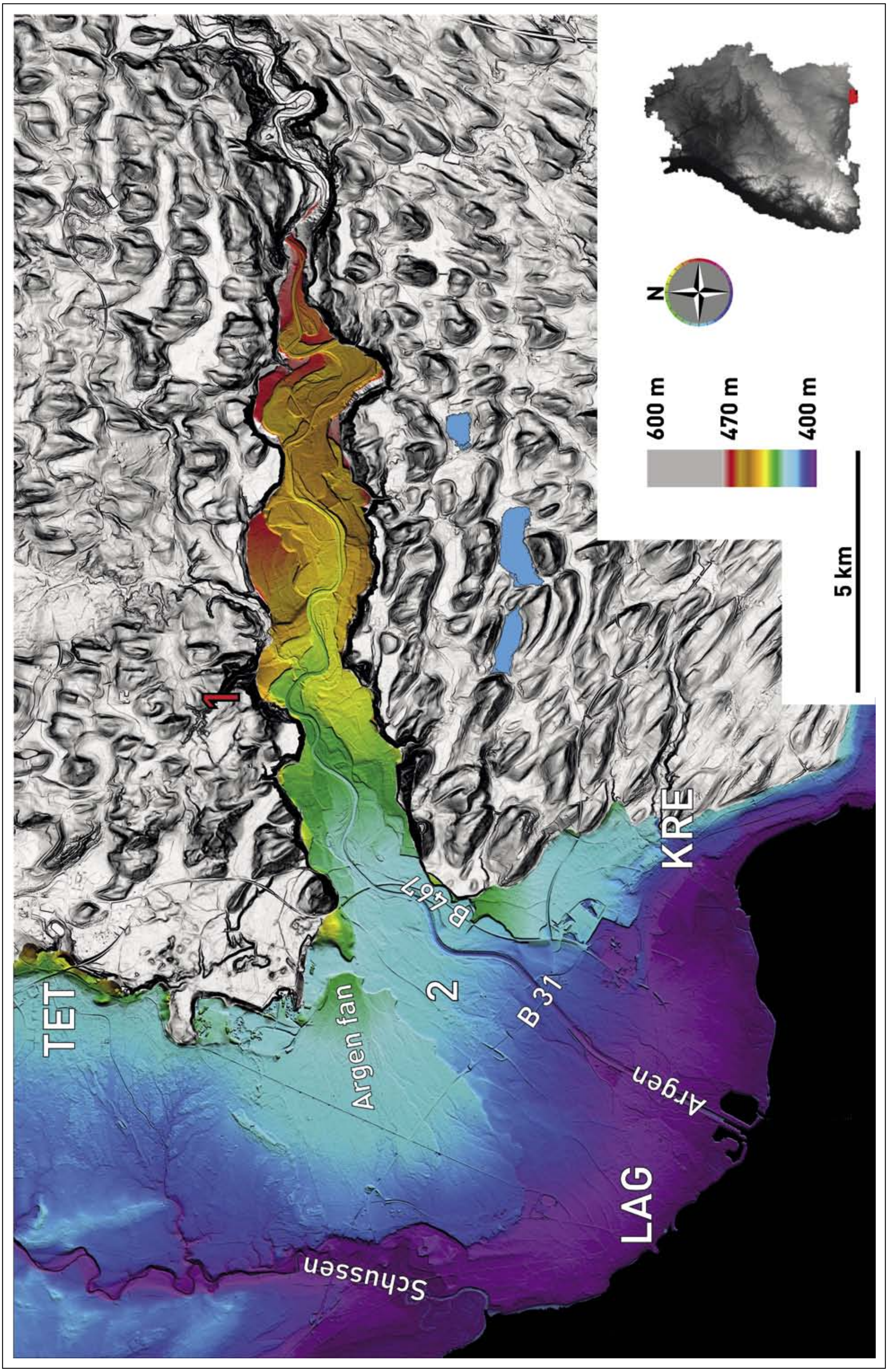
Radially arranged, more or less deteriorated drumlins are an obvious landmark in the southern part of the region of Fig. 8. As in the Aulendorf area (Fig. 4) the occurrence of drumlins in such a position is incongruous with their typical Würmian distribution (restriction to the belt between in the inner Würmian end moraine and the "Konstanzer Stadium", compare Figs. 2 and 9). We conclude that this more or less well preserved fan of drumlins is another relic of older (Rissian) drumlin fields that largely escaped Würmian glacial erosion as a result from reduced shear stress under a thin ice sheet. In addition, the almost complete lack of kettles in this sector suggests very rapid ice retreat which in turn would prevent the drumlin relics from prolonged overprint by ice wastage processes. In the corresponding geological map on scale 1:25000 (Ellwanger et al. 2008) these features are interpreted as Rissian moraine sediments.

4.9 Recessional terraces in the Argen valley

Within our study area the lower parts of the Argen valley display the best-preserved complex pattern of recessional terraces (Fig. 10). Five terraces are expressed in the DTM and also known from geological mapping at a scale of 1:25000 (Schmidt & Münst 1978). Incision among consecutive terraces ranges from 12 m (between old upper terraces) to 3.5 m (between young lower terraces). The valley crosscuts all previous glaciogenic deposits (in this area, almost exclusively high-convexity drumlins, Schmidt 1998). As elsewhere in the Alpine foreland, this type of post-glacial valley started to incise as a consequence of strong meltwater supply following the disappearance of piemont glaciers (Fiebig 1992). Terraces resulted from rapid base level lowering during final glacier retreat towards the Alpenrhein valley. On the background of a dwindling meltwater outflow the valley became swamped with outwash gravel during colder episodes and incised during warmer time spans. In Bavaria, such late glacial terraces ("Spätglazialterrassen") have been dated at 17/18 to 10.2 ka (Doppler et al. 2011). Gradients of older terraces merge towards the Argen Fan (Fig. 10) which in turn is undercut by late incision. For a terrace correlating with the Argen fan Schreiner (1978) reported ^{14}C ages of 8455 and 8660 years before 1950 but it is to be expected that exposure dating of all terraces will result in a much wider age range for the formation of the fan comparable to the ages obtained in Bavaria.

Fig. 10: Post-glacial recessional terraces in the Argen valley; for the regional context, compare Figs. 1 and 2. The Argen incised into a terrain of high-relief drumlins (shown as a gradient map). Drumlins are interspersed with peat swamps or small lakes; basal till base level surrounding the drumlins dips from 540 m in the East to 470 m in the West. The oldest incision undercutting this level is a steep cliff along the valley flanks; where drumlins are dissected, cliff height reaches 80 m (1). The oldest terraces show undercutting in the order of 10 m; towards the younger terraces, undercutting decreases to 3.5 m. The oldest terraces merge towards the Argen Fan which in turn is undercut by late incision caused by a broad system of braided channels (2). The present-day course of the Argen is a single artificial channel. TET: Tettnang, LAG: Langenargen, KRE: Kreßbronn. B 37, B 467: Federal Highways. Black area: Lake Constance. Inset lower right: position within Baden-Württemberg and colour scale. Orthoview; illumination: 100/40; vertical exaggeration: x 8; pixel size: 8 m. Vertical enhancement of gradient map of drumlin fields: x3.

Abb. 10: Postglaziale Terrassenschachtel im Argental; zur geographischen Orientierung vgl. Abb. 1 und 2. Die Argen unterschneidet ein großes Feld hochkonvexer Drumlins (als Gradientenbild dargestellt). Zwischen den Drumlins liegen zahlreiche Torfmoore und Tümpel (blassblau); die Erosionsbasis der Grundmoräne neigt sich von 540 m im Osten auf 470 m im Westen. Die erste Unterschneidung dieser Fläche erzeugte steile Felsabbrüche entlang der Talflanken; wo Drumlins angeschnitten sind, reicht die Kliffhöhe bis 80 m (1). Die ältesten Terrassen belegen eine Übertiefung um etwa 10 m; bei den jüngeren Terrassen sinkt dieser Betrag auf 3,5 m. Die ältesten Terrassen korrespondieren mit der Oberfläche des Argen-Fächers, der selbst wiederum von einem späten verflochtenen Flusssystem unterschnitten wird (2). Die heutige Argen fließt in einem künstlichen Gerinne. TET: Tettnang, LAG: Langenargen, KRE: Kreßbronn; B 37, B 467: Bundesstraßen. Schwarz: Teil des Bodensees.
Lage in Baden-Württemberg und Farbhöhencodierung: unten rechts; Orthoprojektion; Beleuchtung: 100/40; vertikale Überhöhung: x 8; Pixelgröße 8 m; vertikale Überhöhung der Gradientenkarte des Drumlinfeldes: x 3.


TET
LAG
KRE
Argen fan
Argen
Schussen
B 31
B 467
1
2
600 m
470 m
400 m
N
5 km

5 Conclusions

The potential for recognition and correlation of young glacial landforms is very high in a large-area high-resolution DTM rivalling and in places surpassing conventional ground-based geological mapping. In our study area we could identify and map a large variety of phenomena related to the last (Würmian) glaciation. Some of these features are known from literature, but others have not (or only partly) been recognized as such. This is especially true for a) the distinction between crested and kettled moraines, b) the visualization of fluvial facies in outwash plains, c) the recognition of complex suites of subglacial basins shallowing towards the former ice margin, d) the identification of several subglacial valleys and complex suites of channels parallel to the receding ice margin, e) mircromoraines, f) the considerable differences observed in the shape of drumlins and g) the confirmation of fields of deteriorated Rissian drumlins within the area of Würmian glaciation. During our ground checks we realized that digital mapping of morphologic phenomena related to the last glaciation can be very accurate. In fact, as a consequence of comfortable large-distance correlation within the model it turned out that ideas to be tested rather grew from scrutinizing the DTM than out of traditional mapping. The identification of structures related to older glaciations, on the other hand, largely depends on geological field criteria. With the exception of a wide belt of gentle undulating hills most probably representing older (Rissian) drumlin fields overprinted by multiple solifluction processes there are in the DTM only a few morphological traces of older glaciations.

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