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Geoarchaeology and past human–environment interactions

Guest editors: Hans von Suchodoletz, Stefanie Berg, Lukas Werther, Eileen Eckmeier and Christoph Zielhofer

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Preface

Preface: Special Issue "Geoarchaeology and past human–environment interactions"

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1 Geoarchaeology: emerging fields and current challenges

Geoarchaeology incorporates various research areas at the interface between geosciences and archaeology. The discipline had already evolved during the 19th century when concepts of geology and stratigraphy were applied to archaeological contexts, but the use of the term geoarchaeology, and its recognition as an independent discipline, only started in the 1970s and 1980s (Cannell, 2012). However, several definitions of geoarchaeology have been proposed and discussed during the last years, depending on the scientific background of the authors (e.g., Butzer, 1982; Leach, 1992; Rapp and Hill, 1998; Benedetti et al., 2011; Engel and Brückner, 2014). Focusing on the equal role of both sciences, we follow the definition of Tinapp (2013) and define geoarchaeology as the application of geoscientific concepts in archaeology, and also of archaeological concepts in geosciences, to investigate the interactions between humans and geoecosystems during different periods. Geoarchaeology is an approach rather than a technique, so any technique or method can be included as it addresses the understanding of past human activities in a landscape and their environmental context (Cannell, 2012).

Given that humans always lived in landscapes and ecosystems and that those landscapes and ecosystems have been influenced by humans since the beginning of human activity, integrative investigations using a geoarchaeological approach are a mandatory precondition to obtain a comprehensive understanding of past human–environmental interactions. Furthermore, given its regional- to local-scale approach in documenting the often long and intricate history of human–environmental interactions, geoarchaeology is well suited for anthroposphere research that looks at regional landscape changes linked with human activity rather than at global phenomena (Kluiving and Hamel, 2016). The discipline strongly evolved during the last years, and different methods such as micromorphology, palynology, geochemistry, isotopic studies, geographical information systems and geophysics were integrated, leading to very multidisciplinary approaches in which the discontinuities and limitations of one proxy can be overcome by the evaluation of another (Ghilardi and Desruelles, 2009; Cannell, 2012; Engel and Brückner, 2014; Zielhofer et al., 2018; Schneider et al., 2019). Furthermore, geoarchaeology was even established as a subject at different universities (Tinapp, 2013).

However, comprehensive and systematic multidisciplinary geoarchaeological research often remains limited to well-funded scientific research and larger commercial projects, although it contributes to a better understanding of complex human–environment interactions and could improve the sampling strategies (Cannell, 2012). In Germany, for example, most excavations are advance archaeological excavations in the context of construction works that are carried out by state departments of archaeology either on their own or by authorized private excavation companies in agreement with the authorities. The comprehensive and systematic application of geoarchaeological approaches is now slowly being realized at archaeological excavations, which also holds true for its use in the context of other applied archaeological questions such as creating databases for monument preservation (Gerlach et al., 2012; Tinapp, 2013; Beilharz and Krausse, 2015; Nadler, 2019). In addition to the development and integration of innovative methods and the further development of existing geoarchaeological concepts, the application of comprehensive and systematic geoarchaeological approaches in the daily practice of archaeological excavations and monument conservation is therefore a current challenge that must be addressed in the coming years in order to prevent further research gaps and an irreversible loss of potential knowledge.

2 The contributions of this volume

This Special Issue includes studies that were presented at the 15th annual meeting of the German Working Group for Geoarchaeology (Deutscher Arbeitskreis für Geoarchäologie) that was held during May 2018 at the main seat of the Bavarian State Department for Cultural Heritage in Munich. The working group was founded in 2004 and annually unites around 100 geoscientists and archaeologists from different German-speaking universities and research institutions as well as colleagues from state departments of archaeology, private excavation companies and geoarchaeological freelancers. Besides presenting and discussing current geoarchaeological research projects and the integration of new methods into geoarchaeological contexts, one goal of these meetings is to connect geoscientific and archaeological scientists from universities, research institutions and the daily archaeological practice in order to also distribute geoarchaeological approaches within the latter field. According to the broad-ranging interdisciplinary audience of the meeting, the seven articles in this Special Issue report about current geoarchaeological research projects, the application of innovative methods and approaches in geoarchaeological contexts, and issues related to the daily practice of monument management, mirroring the broad range of current developments and challenges in geoarchaeology.

The study of Hensel et al. (2019) was carried out by scientists at the University of Cologne in the framework of the DFG-funded CRC806 project "Our way to Europe". The authors investigated the recent relations between hydrological systems and the distribution of Palaeolithic sites and obsidian raw material outcrops in southwestern Ethiopia by combining geomorphological–hydrological analyses with field surveys and GIS mapping. Doing so, the authors aimed to transfer these recent interrelations into the past to better understand the factors that influenced prehistoric human settlement activity. Although – due to intensive current morphodynamics – a simple transfer of the recent situation into the past seems rather complicated, this study demonstrates an innovative way to deal with geoarchaeological questions such as former raw material availability at larger regional scales.

The study of Miera et al. (2019) was carried out by scientists at the University of Tübingen in the framework of the DFG-funded CRC1070 project "Resource Cultures" and aims to decipher the Neolithic settlement dynamics in several landscapes of southwestern Germany. The authors combined existing archaeological and new archaeopedological data from colluvial deposits. The latter were dated using radiocarbon and luminescence methods and are regarded as indicators of former settlement activity. This study presents an innovative geoarchaeological approach to complement generally incomplete archaeological datasets of former settlement activity, allowing researchers to derive better-based conclusions about the former settlement dynamics.

The study of Tolksdorf et al. (2019) reports about the results of the EU-funded bilateral German–Czech research project "ArchaeoMontan – Mittelalterlicher Bergbau in Sachsen und Böhmen" and was carried out under the leadership of the Archaeological Heritage Office in Saxony. The authors used palaeobotanical and geochemical methods as well as radiocarbon and potsherd dating to reconstruct the Medieval settlement and mining history as well as desertion processes in a small catchment in the Saxon Ore Mountains of eastern Germany. This study is a good example for how geoarchaeological investigations can complement patchy archaeological and historical datasets, leading to a better understanding of historical processes that are not documented elsewhere.

The study of Engel et al. (2020) reports the results of a joint German–Qatari study that was carried out in the southern Qatari peninsula and was led by scientists from the University of Cologne. The authors investigated the current geomorphic setting and palaeoenvironmental changes recorded in karstic depressions that were centers of prehistoric settlement activity at least since the Neolithic period, focusing on the former availability of water resources. By integrating geomorphic mapping, geophysical prospection, sediment coring, sediment analyses and luminescence dating and relating their results with the location of archaeological sites, the authors aim to contribute to building up a palaeoenvironmental framework of prehistoric settlement.

The study of Reichel et al. (2019) was carried out by scientists from the University of Applied Sciences Berlin. It addresses soil erosion at archaeological sites that on the one hand affects the site through destruction processes and on the other hand builds up a record of former agricultural activity in the form of colluvial layers. The authors investigated Late Holocene colluvia in combination with the position of an adjacent lake shoreline next to an archaeological site in eastern Germany by using sedimentological–pedological analyses, tachymetric mapping and archaeological dating of archaeological finds, photogrammetric methods and GIS. The study demonstrates that this combination of methods allows for a more precise stratigraphical classification of archaeological finds in geoarchaeological trenches, leading to a better chronological classification of colluvial layers.

The study of Teegen et al. (2019) is mostly based on field courses for students that were carried out under the supervision of scientists from the Ludwig Maximilian University in Munich. The authors report about archaeological prospections of a Celtic to Roman site in western Germany using a combination of field and geophysical surveys, lidar scans, aerial photographs, and GIS analyses that resulted in kernel density maps of bricks and ceramics. The authors demonstrate that such an integrated methodological approach leads to a significant gain in knowledge about the location of former houses, the way of their destruction and former waste management.

The study of Vogt and Kretschmer (2019) exemplifies the use of a geoarchaeological approach for cultural heritage management. It emerged from the archaeological practice of the Archaeological Heritage Office in Saxony and the State Office for Cultural Heritage Management Baden-Württemberg. The authors address the conflicts between archaeology and agriculture linked with soil erosion and the drainage of wetlands that endanger archaeological sites in intensively used agrarian landscapes. To locate archaeological sites that are affected by soil erosion, the authors use a geoarchaeological approach that includes aerial photographs, soil mapping and soil coring. The use of this knowledge, by incorporating the interests of landowners and farmers, allows researchers to develop individual conservation and protection strategies for endangered archaeological sites.

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Research article

Combining geomorphological–hydrological analyses and the location of settlement and raw material sites – a case study on understanding prehistoric human settlement activity in the southwestern Ethiopian Highlands

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Abstract: During this study, the recent relations between the hydrological systems and the distribution of archaeological sites and obsidian raw material outcrops within the catchment of the Bisare River, around Mt Damota, and around Mt Sodicho in the southwestern Ethiopian Highlands were investigated. To do so, we combined geomorphological–hydrological analyses with field surveys and GIS mapping. The aim was to try to transfer these recent interrelations into the past to better understand the factors that influenced prehistoric human settlement activity. The natural geomorphodynamics in landscapes such as the southwestern Ethiopian Highlands were and still are characterized by the interplay between endogenous processes (tectonics, volcanism) and climatic fluctuations and, during the recent past, also by human activity. In the considered region, protective and potentially habitable rock shelters are found at the volcanic slopes of Mt Damota and Mt Sodicho at high elevations. In addition, in some areas recent morphodynamic processes make obsidian raw material available near the surface. However, archaeological and terrestrial paleoenvironmental archives that allow an understanding of the interplay between prehistoric settlement activity and paleoenvironmental conditions are still rare. Therefore, the surroundings of formerly occupied rock shelters were investigated to illustrate the effect of the recent fluvial morphodynamics (erosion and accumulation) on surface visibility and preservation of archaeological obsidian raw material. This recent information can be used to make assumptions about the former hydrological system and to thereby get answers to research questions such as those about the past accessibility of obsidian raw material for prehistoric humans. The results suggest that the study area is currently affected by a highly dynamic hydrological system, which is indicated by phenomena such as the formation of swamps due to sedimentation in natural depressions. In addition, wide areas of the Bisare River catchment are affected by gully erosion, which leads to land degradation but also to the exposure of the above-mentioned lithic raw material outcrops. Human influence strongly increased during the Holocene until today, especially on the mountain flanks. This in turn increased soil loss and erosion of archaeological sites, which complicates the transfer of the current morphodynamics into the past. Although it cannot be finally confirmed that prehistoric hunters and gatherers systematically used fluvially exposed raw material, based on our results it can be assumed that humans frequented this area, due to the local availability of such kind of material.

Kurzfassung: Im Rahmen dieser Studie wurden die aktuellen Zusammenhänge zwischen hydrologischen Systemen, sowie der Verbreitung archäologischer Fundplätze und von Obsidian-Rohmateriallagerstätten im Einzugsgebiet des Bisareflusses, um Mount Damota sowie um Mount Sodicho im südwestlichen äthiopischen Hochland untersucht. Hierfür wurden geomorphologisch-hydrologische Analysen mit Geländesurveys und Gis-Kartierungen kombiniert. Das Ziel war der Versuch, die aktuelle Situation in die Vergangenheit zu übertragen, um die prähistorische menschliche Siedlungsaktivität besser zu verstehen. Das natürliche geomorphologische Prozessgeschehen in Landschaften wie dem südwestlichen äthiopischen Hochland wurde und wird durch das Zusammenspiel von endogenen Prozessen (Tektonik, Vulkanismus) sowie Klimaschwankungen und in jüngster Zeit auch durch menschliche Aktivitäten geprägt. In der betrachteten Region finden sich höher gelegene, schützende und potentiell bewohnbare Felsüberhänge (Rockshelter) an den Vulkanhängen des Mt. Damota und des Mt. Sodicho. Außerdem wird durch aktuelle morphodynamische Prozesse in einigen Bereichen Obsidian als Rohmaterial oberflächennah verfügbar. Archäologische und terrestrische Paläoumweltarchive, die es ermöglichen, das Zusammenspiel zwischen prähistorischer Besiedlung und Umweltbedingungen zu verdeutlichen, sind jedoch noch selten. Daher wurde die Umgebung der ehemals bewohnten Rockshelter untersucht, um die Auswirkungen der rezenten fluvialen Morphodynamik (Abtragung und Akkumulation) auf die oberflächennahe Sichtbarkeit und Erhaltung archäologischer Rohmaterial-Fundstellen zu verdeutlichen. Die gewonnen Informationen können dafür verwendet werden, Annahmen über das ehemalige hydrologische System zu treffen und somit Antworten auf Forschungsfragen wie jener nach der ehemaligen Zugänglichkeit von Obsidian-Lagerstätten für den prähistorischen Menschen zu erhalten. Die Ergebnisse legen nahe, dass das Untersuchungsgebiet derzeit von einem hochdynamischen hydrologischen System geprägt wird, was sich beispielsweise durch Phänomene wie der Ausbildung von Sümpfen aufgrund von Sedimentation in natürlichen Depressionen zeigt. Darüber hinaus stehen weite Bereiche des Einzugsgebiets des Bisareflusses unter dem Einfluss von Gullyerosion (Grabenerosion), welche zu Bodendegradierung und zur Freilegung der oben genannten lithischen Rohmaterialien führt. Insbesondere an den Bergflanken nahm der anthropogene Einfluss während des Holozäns stark zu. Dies wiederum verstärkte den Bodenabtrag und die Erosion archäologischer Fundstellen, was den Transfer der aktuellen Morphodynamik auf die Vergangenheit erschwert. Obwohl nicht eindeutig nachgewiesen werden kann, dass prähistorische Jäger und Sammler fluvial freigelegtes Rohmaterial gezielt nutzten, kann basierend auf unseren Ergebnissen davon ausgegangen werden, dass die lokale Rohmaterialverfügbarkeit zu einer verstärkten Frequentierung der Region durch prähistorische Menschen führte.

1 Introduction

The landscape of the southwestern Ethiopian Highlands was created by tectonic stresses and Late Pleistocene–Holocene eruptive activity, as well as by the increasing influence of human activity in recent times. The development of topographic barriers and natural basins that were induced by tectonic uplift or faulting created a complex relief with ridges and ravines (De La Torre et al., 2007; Benito-Calvo et al., 2007). Large areas of today's surface are influenced by erosional processes, for example, by widespread gully erosion and badlands formation that are common causes of morphological transformations in Ethiopia today (Billi and Dramis, 2003). In many cases, this development is linked to human influence and the intensification of agriculture (Castillo and Gómez, 2016). Up to now, there are only a few terrestrial geoarchives in East Africa with reconstructions of Pleistocene and Holocene precipitation or temperature changes (Tierney et al., 2008; Tierney et al., 2011; Foerster et al., 2012, 2015). Due to the rare paleoclimatic data but also due to the lack of valuable archaeological information, there is still an ongoing discussion on how short- and long-term climatic events and trends affected prehistoric humans living on the Horn of Africa. Available paleoclimatic records from lake sediments from Ethiopia and Kenya document wet–dry transitions that likely affected prehistoric humans and their adaption to the changing environment. In this context, one proposed hypothesis is the retreat of human groups into highland regions with higher precipitation rates during dry periods (Basell, 2008; Foerster et al., 2015; Junginger and Trauth, 2013).

Our study discusses the following research questions. (1) How does the actual hydrological system of the study area look like? (2) What role does this system play in present accessibility of obsidian raw material sources and the visibility and preservation of archaeological sites? (3) Which geomorphological features related to erosion are present? (4) Can we make assumptions about the ancient hydrological system and landscape dynamics and, on their influence, on the accessibility of past obsidian raw material sources? For our studies we selected three research areas in the southwestern Ethiopian Highlands, ca. 250 km southwest of Addis Ababa, that are located within a radius of 40 km of one another (Fig. 2). (1) Mt Damota is a volcanic mountain that became of archaeological interest because of its key site, the Mochena Borago Rockshelter, which is one of the most important Late Pleistocene and Holocene sites in eastern Africa (Brandt et al., 2012). (2) Mt Sodicho is located ca. 40 km to the northwest of Mt Damota and marks the second research area. The archaeological site Sodicho Rockshelter is located on the southern flanks of this volcanic mountain. (3) The banks of the Bisare River, a tributary of the Bilate River, are located southeast of Mt Damota (Fig. 2a).

Archaeological records within the rock shelter sediments of, e.g. Mt Damota or Mt Sodicho, provide information about ancient human–environment interactions. Additionally, numerous open-air sites at the slopes of Mt Damota provide a complementary record of former human settlement (Brandt et al., 2012; Vogelsang and Wendt, 2018). The main trench at Mochena Borago yielded three major lithostratigraphic units with archaeological material classified as Middle Stone Age (MSA), dating to ages between 36 and >50 ka (Brandt et al., 2017). However, a sedimentological hiatus in the stratigraphy from ~ 36 to ~ 8 ka leaves unanswered questions about deposition processes and the occupation at that site until the Holocene (Brandt et al., 2012, 2017). Vogelsang and Wendt (2018) examined multiple archaeological surface localities classified as MSA and Late Stone Age (LSA) sites on the western flank of Mt Damota to reconstruct prehistoric settlement patterns. They recognized intensification of settlement activities from the MSA to the LSA, as well as a different organization of the site clusters along the mountain slopes. Whereas the reconstructed MSA settlement areas show a linear, vertical orientation and include different altitudinal belts, the LSA sites form one large cluster with interconnected smaller sub-groups. The former is interpreted as a land use model that offered short access to various eco-zones in different elevations, a strategy that might have been advantageous during times of environmental stress. Following our first results for the Sodicho Rockshelter, archaeological settlement layers with preserved and recently dated lithic material fill the Late Pleistocene and Holocene occupational gap (~ 36 to ~ 8 ka) from Mochena Borago. Generally, the volcanic rocks of Mt Damota and Mt Sodicho do not contain any naturally occurring obsidian, although this is the most common raw material used for the production of stone artefacts at all archaeological sites in the region (Brandt et al., 2012, 2017). The third study area at the permanent Bisare River site shows a high potential for geoarchaeological investigation (Benito-Calvo et al., 2007), since obsidian raw material was exposed by gully erosion and archaeological artefacts from all stone age periods are scattered within the catchment area. The main causes of gully formation and further development are still not clear, although several factors are potentially relevant for the development of this incision. These often include, e.g. higher precipitation after arid phases, loose topsoil material, and sparse vegetation due to intense land use (Billi and Dramis, 2003; Fryirs and Brierley, 2013; Mukai, 2017). By studying swamp formation in the upper Bisare catchment, the influence of alternating wet and dry phases on the regional landscape dynamics could exemplarily be investigated for the last several years (for long-term climatic fluctuations, please compare Trauth et al., 2019). These alternations lead to changes in erosion and deposition. Generally, our analysis of the landscape archive at the Bisare River sheds light on site preservation and raw material availability.

In order to understand ancient human–environment interactions, understanding the past morphodynamics is crucial. We followed a diachronous approach and tried to transfer today's knowledge about the local fluvial dynamics that affect archaeological assemblages and raw material outcrops by degradation into the past. In the framework of this study we applied geomorphological and hydrological analyses via remote sensing and field surveys. In doing so, we mapped the current flow directions and stream networks and compared these with signs of former human occupation.

2 General settings of the study area

2.1 Geological and geomorphological setting

The study area is located in the southwestern Ethiopian Highlands north of Lake Abaya, between the north–south-running Omo River in the west and the Bilate River in the east, at the border of the western central and southern Main Ethiopian Rift and the southern Ethiopian Plateau (Fig. 1b). On average, the mountain ranges rise to 2000–3000 m above sea level (a.s.l.). Plio–Pleistocene volcanic activity and Late Pleistocene to Holocene tectonic stress formed characteristic natural basins, steep slopes, and gorges. Silicic volcanic material, including the trachytic solid rocks of Mt Damota and

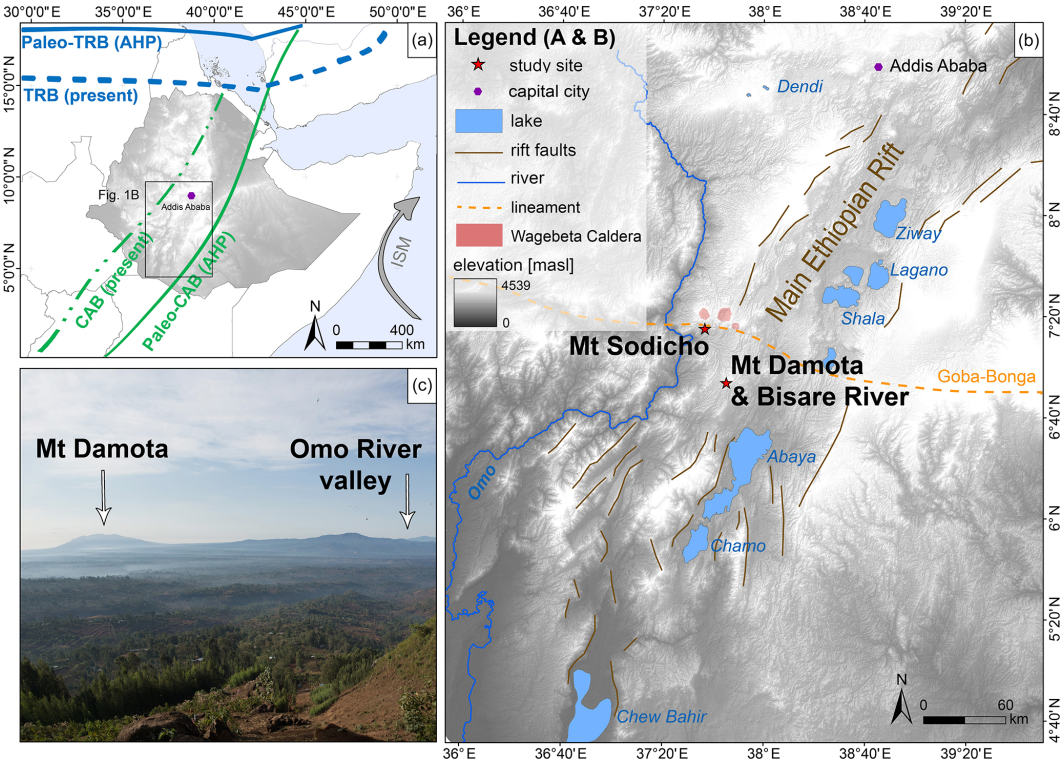

Figure 1. **(a)** Map showing the flow of the Indian Summer Monsoon (ISM) and the current northernmost position of the tropical rain belt (TRB) during August (TRB, present) and its shifted northernmost position for August during the African humid period (Paleo-TRB, AHP, ∼ 15 ka BP to ∼ 5 ka BP). The map also refers to the present position of the Congo Air Boundary (CAB) and its shift during the AHP (modified from Junginger and Trauth 2013). **(b)** Research area at the rift margins in the southwestern Ethiopian Highlands, showing the major geological fault system of the Main Ethiopian Rift, the big lake systems, the Wagebeta Caldera Complex, and the Goba-Bonga lineament. The study sites are marked by red stars (DEM data by ASTER GDEM; illustration by Elena Hensel). **(c)** Photo taken from the southern flank of Mt Sodicho, showing the silhouette of Mt Damota and the Omo River valley (viewing direction south-southwest) (Photo by Christian Schepers, illustration by Elena Hensel).

Mt Sodicho, is part of the rift shoulder trachytic volcanism, which developed in the Pliocene during the late stages of the formation of the Ethiopian Rift (Chernet, 2011; Corti et al., 2013; Abbate et al., 2015).

Mt Damota is a dormant igneous volcanic mountain with a height of 2908 m a.s.l., which is primarily composed of greenish grey trachyte (Brandt et al., 2012). It is part of a larger silicic complex and overlies a pyroclastic rock formation of rhyolitic to trachytic lava and ignimbrites that are associated with the Nazret Group (Chernet, 2011; Corti et al., 2013). Woldegabriel et al. (1990) assumed a formation of the trachytic flows of the volcano during the Late Pliocene (∼ 2.9 Ma). Mt Sodicho, with an elevation of about 2100 m a.s.l., belongs to the Wagebeta Caldera Complex (Fig. 1b). The mountain lies directly on the Goba-Bonga lineament, a transversal east–west depression with transversal structures that crosses the Main Ethiopian Rift (Bonini et al., 2005; Corti, 2009; Corti et al., 2013). The Bisare River catchment is situated southwest of Mt Damota within the Hobitcha Caldera structure (Fig. 2c). The river is a western tributary of the Bilate River that flows into the northern part of Lake Abaya. This lake is located in a quasi-endorheic basin (Schütt et al., 2005). The Bisare River is associated with glacis and valley fills including interbedded volcanic rocks. The latter are not older than 200 ka and developed from the Middle to Upper Pleistocene up to the Holocene (De La Torre et al., 2007). Archaeological finds in the area of the Bisare River catchment comprise open-air artefact scatters and widespread raw material locations, which are currently exposed as a result of river incision (Benito-Calvo et al., 2007; De La Torre et al., 2007; Abbate et al., 2015; Vogelsang, unpublished observation, 2011, 2012).

2.2 Climatic setting

The Ethiopian Highlands receive more than 2000 mm of annual rainfall, which is the highest average amount at the Horn of Africa (Griffith, 1972; Viste and Sorteberg, 2013). Annual climatic variations in Ethiopia are related to moisture brought by the summer monsoon that interacts with the dry northeastern "Harmattan" wind system and to changes in the north–south directed pressure gradient (Viste and Sorteberg, 2013; Nicholson, 2018). A further influence is changes in sea surface temperatures of the adjacent Indian Ocean (Griffith, 1972; Tierney et al., 2008; Segele et al., 2009; Viste et al., 2013). Inter-annual changes in precipitation are linked to the shifting of the tropical rain belt (TRB), low-level convergences, and the role of the accentuated topography (Nicholson, 2018) (Fig. 1a). The Congo Air Boundary (CAB) is an additional but less relevant source for moisture variability in Ethiopia (Junginger and Trauth, 2013). Most of the annual precipitation (50 %–90 %) falls during boreal summer from June to September, called "Kirmet" in this area. Regions with the highest precipitation receive up to 350 mm of rainfall per month (Berhanu et al., 2013). The vegetation of the study area around Mt Damota and Mt Sodicho encompasses two classification types according to Friis et al. (2010): grasslands and mountainous woodland between 1600 and 3300 m a.s.l. belong to the "dry evergreen montane forest and grassland complex" classification and evergreen trees between 1500 and 2600 m a.s.l. to the "moist evergreen montane forest" classification. The mountain flanks of Mt Damota and Mt Sodicho were reshaped by human deforestation, intensive subsistence farming, and subsequent partly severe soil erosion during the last few decades (Fig. 1c). The paleoclimate of southwestern Ethiopia of the last 45 ka was characterized by fluctuations of moister and drier conditions (Foerster et al., 2012; Trauth et al., 2019). According to the paleoclimate record of the Chew Bahir drill cores, arid conditions during the Last Glacial Maximum (LGM, ∼ 24–18 ka) led to a desiccation of the former paleolake (Foerster et al., 2012, 2015; Trauth et al., 2019) (Fig. 1b). Subsequently, an abrupt change is visible after ∼ 15 ka with a transition from extreme arid to humid conditions, marking the starting point of the African humid period (AHP, ∼ 15 to 5 ka). This was a period with a generally higher and stable availability of moisture but was, however, interrupted by several dry spells. Exemplary arid phases were the Older Dryas stadial (OD, ∼ 14 ka) and the Younger Dryas event (YD, 12.8–11.6 ka), followed by shorter dry events (∼ 10.5, ∼ 9.5, 8.15–7.8 and ∼ 7 ka). The end of the AHP was marked by an increase in aridity that persists to this day. Exceptions were short humid events at ∼ 3, ∼ 2.2, and 1.3 ka (Foerster et al., 2012, 2015).

3 Material and methods

3.1 Mapping and survey

The research areas around Mt Damota and Mt Sodicho were mapped during field surveys from 2015 to 2018 that were supported by high-resolution satellite imagery. Geomorphological mapping in the field included the description of rock outcrops, surface exposures, geomorphological features, and signs of the influence of extensive modern human occupation in the area. Afterwards, topographical features such as reliefs and slopes, as well as drainage ways and further geomorphological properties, were extracted from a high-resolution digital elevation model (DEM) (Sect. 3.2). Archaeological surveys in the surrounding area of Mt Damota were conducted from 2010 to 2014, resulting in the discovery of 63 open-air sites. The surveys included different landforms of the tropical highlands in various altitudes, following "stratified random sampling" (Shafer, 2016; Vogelsang and Wendt, 2018). Systematic archaeological and geomorphological surveys of the western Bisare River and Bilate River were undertaken in 2006 by the research group around De la Torre et al. (2007) and in 2011, 2012, and 2014 by the research team of the Collaborative Research Centre 806 (CRC806) "Our way to Europe". The excavations at Sodicho Rockshelter on Mt Sodicho started in 2015.

3.2 GIS-based analyses

The image analysis software ENVI (5.3 by Harris Geospatial Solutions) was used to extract high-resolution digital elevation models (DEM) using panchromatic images of Pléiades 1A (by Astrium Services/Spot Image, Airbus Defence and Space) satellites, with a 2 m resolution, and ASTER GDEM data (by METI and NASA), with a resolution of 30 m. For this, identical tie points on both satellite images were manually fitted together to create panchromatic images. The high-resolution DEMs generated from the Pléiades satellite scenes cover areas spanning Mt Sodicho, Mt Damota, and the Bisare River catchment, and singular ASTER scenes were used to fill gaps.

Surface and hydrological data were determined by a Geographical Information System (ArcGIS 10.6 by ESRI) using the beforehand-created DEMs functioning as base "maps". The modelling tools of Arc Hydro (ESRI) were used for the extraction of the hydrological features, such as flow direction and accumulation, surface runoff, and catchment areas. The calculated GIS data sets can be requested from the CRC 806 Database via https://doi.org/10.5880/SFB806.49. These parameters allowed a quantitative raster- and vector-based calculation of the actual drainage systems (Bolten et al., 2006). Freely available satellite images of the Google Earth Timelapse NASA Landsat programme from 2009 to 2017 were used to identify annual landscape transformations, i.e. swamp formation and reduction (Fig. 3). In addition, viewshed analyses from both mountaintops (Mt Damota and Mt Sodicho) were conducted with ArcGIS 10.6 (ESRI) to test the significance of the archaeological rock shelters at high evaluations and their importance for prehistoric hunter-gatherers. To do so, a body height of 1.60 m was defined.

3.3 Radiocarbon dating

Several percussion drilling cores were obtained from 11 drilling locations in the basin of the Bisare River swamps in 2014 and 2015. The drilling locations were placed over the entire swamp area. Drilling locations in the surrounding area were not considered, since the surroundings are dominated

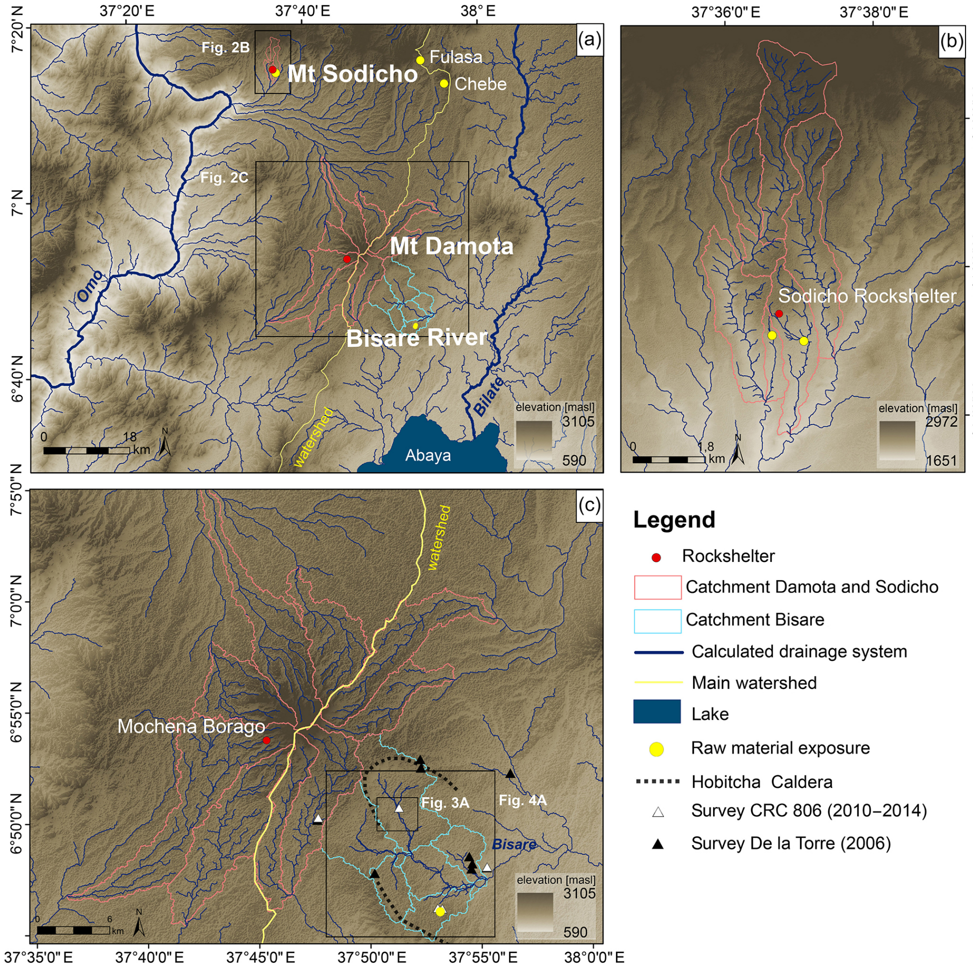

Figure 2. **(a)** Map showing the calculated drainage networks in the study area for the three study sites: Mt Damota, the Bisare River catchment, and Mt Sodicho. Primary drainage systems mainly support the two major south running rivers: Omo and Bilate. **(b)** Drainage network at the southern flank of Mt Sodicho. **(c)** Drainage network of Mt Damota and the Bisare River. The triangles illustrate archaeological evidence mapped by De la Torre (2006) and by the CRC 806 (2010–2014) (DEM data from Mochena and Bisare by ASTER GDEM; DEM data from Sodicho by Astrium's Pléiades; illustration by Elena Hensel).

Table 1. Radiocarbon ages for the samples from the BIS03 and BIS07 drilling cores.

Sample label	Sample ID	Material	Depth b.s.l. (cm)	Age (years BP)	±	Age (years CE)	$\delta^{13}C$ (‰)
COL2819.1.1	BIS03-RC1	plant	118	−325	34	n/a	−28.6
COL3300.1.1	BIS07-C1_W	plant	280	> modern	–	1957–1998	−11.2
COL3301.1.1	BIS07-C1_S	sediment	280	25	35	1694–1919	−21.2

n/a: not applicable.

by modern agriculture and therefore excessively influenced by human activity. In this study, we present three samples from cores BIS03 and BIS07 of the uppermost part of swamp 1, which were tested for radiocarbon dating (Table 1). Both cores were drilled in fluvial sequences located on the edges of the swamp (Fig. 3a). The three radiocarbon samples, from either plant (BIS03-PC1 and BIS07_W) or sediment material (BIS07-C1_S), were extracted from silty to sandy sediments in the upper 3 m of the drilling cores. The radiocarbon AMS lab of the University of Cologne analysed the samples with acid and alkali (AAA) pre-treatment to remove inorganic carbon and humid acids. The conventional radiocarbon ages were calibrated with OxCal v. 4.2.3, applying the calibration curve IntCal13 (Ramsey et al., 2013; Reimer et al., 2013).

4 Results

4.1 GIS-based analyses

The geomorphological and hydrological analyses of the two mountains and the Bisare River catchments were based on high-resolution DEMs that were calculated based on remote sensing data. With the help of the catchment analysis, recent large-scale drainage lines of the study area around Mt Damota and Mt Sodicho were defined (Fig. 2a). In combination with a geomorphological field survey, small-scale and large-scale gully erosion could be identified.

1. Mt Damota has a typical radial drainage system, which is crossed by a main watershed (Fig. 2c). This watershed is running north–south through the entire study area, separating the runoff into a western and an eastern direction. The western streams drain into the Omo River basin, whereas the eastern streams drain towards Lake Abaya but without an inflow into the Bisare River catchment. This is caused by the horseshoe-shaped Hobitcha Caldera that functions as a barrier between the eastern streams and the Bisare River catchment.

2. Mt Sodicho's stream network and drainage lines mainly flow into the Omo River basin. According to the hydrological analyses and the field observations from 2017, Mt Sodicho has a radial drainage network, which gave the mountain its characteristic irregular form (Fig. 2b). Permanent streams and seasonal creeks (only flowing during the rainy season) flow down the mountain flanks into a larger south-running dendritic drainage network that belongs to the drainage network of the Wagebeta Caldera Complex. Nowadays, the surface morphology on Mt Sodicho is influenced by intensive agriculture. Small-scale surface erosion (10–20 m in width) was mapped on the upper slopes (Fig. 1c). In the past, the vegetation was probably removed to create cultivation areas, which are now jeopardized by increasing erosion. These active gullies are currently used as pathways for the local population and their cattle, which further enhances degradation and runoff. Raw material provenance of lithic artefacts that were found at Mt Sodicho is still not proven. So far, obsidian raw material with distinct signs of transport could be observed as fluvially transported boulders or debris along the surrounding drainage systems and river banks. In Fig. 2b, these raw material findings are illustrated as yellow dots. Additionally, two obsidian outcrops were discovered to the east of Mt Sodicho during the latest survey in November 2018. Within a distance of 30–36 km from Sodicho Rockshelter, the two outcrops named Chebe and Fulasa were still in the range of movement of the Late Pleistocene hunter-gatherers (Fig. 2a).

3. The Bisare River flows into the Bilate River. The latter is the main tributary of the 15 000 km^2 large catchment of Lake Abaya (Chernet, 2011). Based on the hydrological and geomorphological analyses, different geomorphic features could be observed (Fig. 2c): the research area lies within a dynamic hydrological system, showing a high to moderate runoff of surface water (Berhaun et al., 2013). With the help of a longitudinal profile, starting at the Bisare River catchment and following the Bilate River into Lake Abaya, a sudden change in the slope (knickpoint) could be identified. This knickpoint is situated ∼ 15 km along the profile, where the river flows out from the Hobitcha Caldera (Fig. 5). The study of knickpoints can be used to identify potential areas for sedimentation. Three connected swamps of different sizes and altitudes formed in low-energy parts of the river valley in the upper part of the catchment (Fig. 3). They were documented during geomorphological field mapping in 2014. A highly exaggerated longitudinal profile, running transversely through the lakes, illustrates the local stair-like morphology. Unlike swamp 3, the two upper basins of swamps 1 and 2 are situated in an area with highly dynamic permanent and episodic streams. Via satellite imagery (Google Earth Timelapse NASA Landsat programme), we observed that the two upper swamps are supplied by episodic tributaries during wet seasons (Fig. 3b–d). Gully erosion and sheetwash erosion are widespread phenomena particularly in the lower part of the Bisare catchment (Fig. 4a). Here, surface runoff and erosion-outcropped artefact assemblages are predominantly from the Middle Stone Age (De La Torre et al., 2007). These assemblages were preserved in Pleistocene alluvial soils at the flanks of the river basin. Also, outcrops of in situ obsidian raw material and scattered lithic surface finds were found by De La Torre et al. (2007) and our research team in the southern degraded areas. Formerly buried material was exposed to the surface, and the lithics had been partly transported due to constant erosion and extensive badlands formation, mainly at the lower part of the river catchment. Erosion and badlands formation initiated from the edge of the rift valley and spread upstream of the Bisare (Fig. 4c–e). Figure 4d and e visualize subsurface material cropping out in this degraded area, which varies between reddish-brown regolith and greyish ignimbrite.

According to the viewshed analyses from the mountaintops of Mt Damota and Mt Sodicho, all-round views over the landscape are possible. The views reach from the lakes of the central Main Ethiopian Rift Valley in the distant north, over the Bilate River in the east, Lake Abaya to the south, the Gibe and Omo river valleys to the southwest, and up the Wolayta–

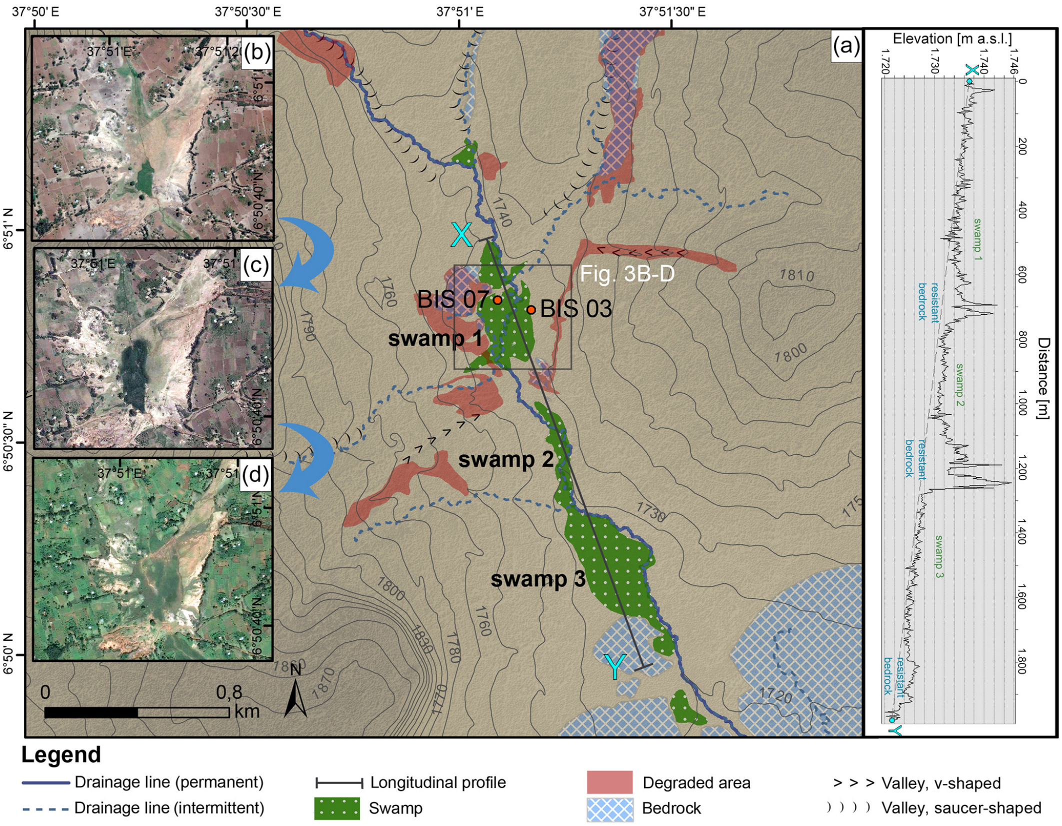

Figure 3. **(a)** Map showing the dimension of the three swamps on the Bisare River. The positions of the two drillings in swamp 1 are marked with red dots (DEM data by ASTER GDEM). The sequence of images **(b)**–**(d)** illustrates the changes of swamp 1 during different wet and dry phases: **(b)** following a dry season (21 March 2009), **(c)** following a wet season (15 November 2009), and **(d)** during a wet season (17 October 2014) (swamp data set by Svenja Meyer; Satellite images by ©Google Earth Timelapse NASA Landsat programme). The super-elevated longitudinal profile X–Y illustrates the geomorphological position of the swamps in the Bisare River basin, leading to a step-like topography, extracted from the DEM based on Pléiades 1A satellite imagery (DEM data by ASTER GDEM; illustration by Elena Hensel).

Hadiya Highlands to the west. During clear weather conditions, the opening area of the Sodicho Rockshelter offers a complete view to Mt Damota and the Omo River basin in the west (Fig. 1c). The view directly from Mochena Borago is limited to the southeast and east, and therefore Mt Sodicho is out of sight. These results verify a locational advantage of both rock shelters, i.e. Mochena Borago on Mt Damota and Sodicho Rockshelter on Mt Sodicho, for watching game in the surrounding lowlands.

4.2 Radiocarbon dating

The modern radiocarbon ages of two botanical samples (BIS03-PC1 and BIS07_W) and one sediment sample (BIS07-C1_S), originating from two drilling cores taken in a depth of up to 2 m below the surface level in the uppermost part of swamp 1, revealed that the upper 3 m of the sedimentary basin fill are of modern age (Table 1). This demonstrates a high sedimentation rate at least in this swamp.

5 Discussion

Several processes of degradation, such as gully or river erosion, led to the exposure of obsidian raw material localities and open-air sites with scatters of stone artefacts (Fig. 4a–d). This is particularly true in the Bisare River basin with its areas of different stream energy where the swamps form sediment traps for the eroded material today. One main question was why these step-like swamps formed and if their formation process can be used to obtain paleoenvironmental information. We propose that during wetter phases stronger gully erosion is activated, and resulting sediment slugs are able to hold up further sediment flux. This can be described as a cut-and-fill process with sediment accumulation in times with relatively intensive erosion and active gullying, and channel incision in periods of less active gullying, e.g. less intensive erosion (Nanson and Croke, 1992; Brierley and Fryirs, 1999; Fryirs and Brierley, 2013; Orti et al., 2019). The consequence is swamp development due to damming of the stream and sediment trapping. Therefore, this area can be assumed to

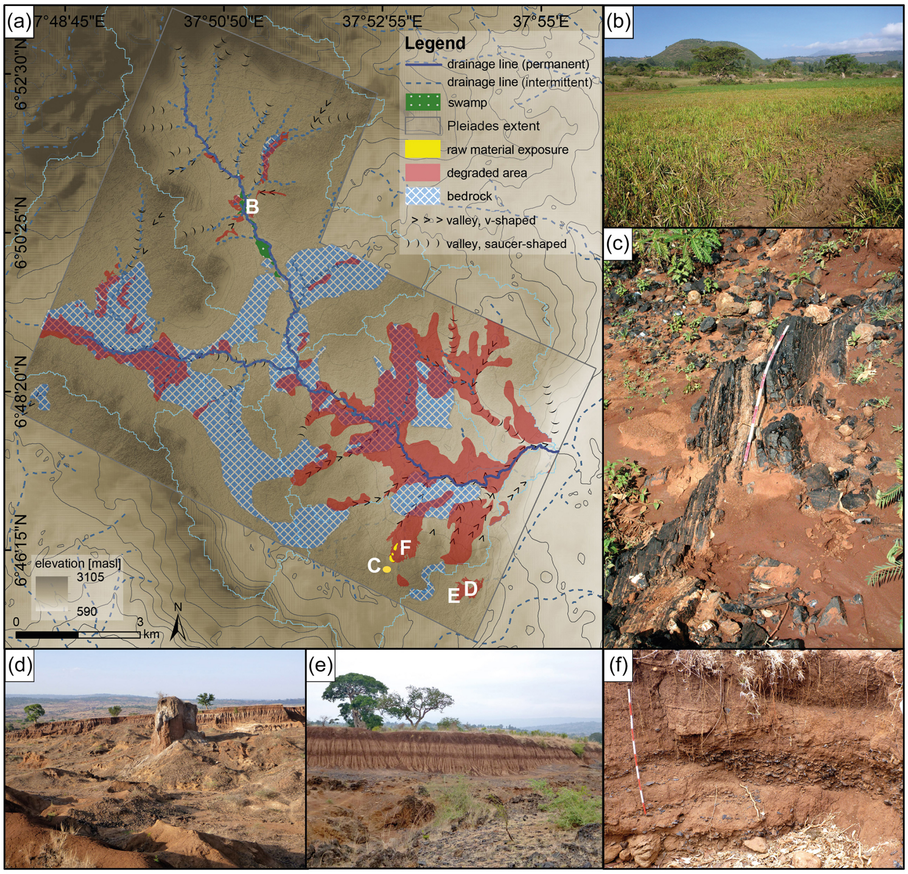

Figure 4. **(a)** Map showing the Bisare River catchment. Degraded areas are mainly characterized by gully erosion. **(b)** Image of the wet, swampy area in the upper part of the catchment (swamp 1). **(c)** Obsidian raw material outcrop. **(d)** Badlands formation and gully erosion is a common phenomenon in the depressions of the catchment. **(e)** Gully-erosion-exposed paleosols alternating with volcanic ash. **(f)** Relocated obsidian flakes exposed in a gully of a degraded area (swamp data set by Svenja Meyer; photography by Olaf Bubenzer; illustration by Elena Hensel).

be very sensitive towards external changes and disturbances, e.g. a change in sediment flux rate. The southernmost part of swamp 3 has the widest dimension, which is most probably the result of a change of bedrock (Fig. 3). A more resistant rock type must have created a natural "bottleneck", which caused natural damming that was intensified by additional damming by sediment slugs during certain periods. As a consequence, the slow-moving water got dammed up, leading to sedimentation and preventing erosion of these accumulated sediments (Machado, 2015). Generally, changes of sediment supply from tributaries into the Bisare and then into the Bilate River must have had a significant geomorphological effect on the main hydrological system in the form of the incision and subsequent aggradation of transported material. In summary, we view this as a geogenic sediment cascade system, where relatively young sediments should have been transported into the lower basin only after the higher basins were filled up (Fig. 3a) (Fryirs and Brierley, 2013; Fryirs, 2016). However, the radiocarbon samples (BIS07-C1) of the sediment in the uppermost basin yielded modern ages, although they are assumed to contain the oldest sediments (Table 1). With a possible sediment cascade and our radiocarbon dates in mind, we state that the development of the swamps must be a relatively recent phenomenon that is linked with the current high erosion and accumulation rates in the area of the Bisare River. Therefore, we suggest that the surficial Pleistocene deposits that are currently largely being exposed by badlands formation in the region must have been completely removed by fluvial erosion, leading to formation of the basins. Afterwards, the basins were refilled by the recent fine-grained sediment that we dated with radiocarbon (Table 1).

With respect to the present-day lithic raw material accessibility and preservation, our geomorphological field observations from 2014 and 2015 coincide with the published observations by Vogelsang and Wendt (2018) on obsidian outcrops in the Humbo area of the Bisare River catchment (Fig. 2c). These authors state that the predominance of obsidian for the production of stone artefacts is not surprising, considering the proximity of the rich sources in the Humbo area to known archaeological sites (Vogelsang and Wendt, 2018). Furthermore, the glassy structure of the obsidian allows a very precise production of lithic tools (Rapp, 2009). Together, this could explain the extreme dominance of obsidian in all lithic assemblages. However, the question arises whether the activity of the hydrological system and erosion processes at Bisare are had a comparable intensity during Late Pleistocene and early Holocene to mid-Holocene, leading to the exposure of a similar amount of raw material. If this was not the case, hunter-gatherers were not able to focus only on the local obsidian deposit in the Humbo area but had to select alternative sources. In this context, also the effects of today's vegetation have to be considered. Today's intensive farming and deforestation, e.g. at the flanks of Mt Sodicho, strongly changed the actual surface runoff but might also directly destroy archaeological deposits. The current destruction and relocation of raw material is visible in the form of scattered obsidian debris and large boulders found along the streams at Mt Sodicho (Fig. 2b). At the moment, we cannot verify if prehistoric hunter-gatherers were able to use such kinds of displaced raw material, but this would be an interesting question for future research. Generally, we think that understanding the hydrological system is fundamental for the evaluation of obsidian raw material availability in this area. However, we still do not know the rate and the start of gully erosion and badlands formation in our study area that are known as inhomogeneous processes – in intensity as well as in duration (Castillo and Gómez, 2016). If the Late Pleistocene hydrological system was as highly dynamic as it is today, gully erosion might have already been initiated by natural processes during that period. We only expect this for certain climatic phases in which the paleoenvironmental conditions promoted such a dynamic system due to higher precipitation. Accordingly, several studies demonstrated variable climatic conditions at the Horn of Africa during the Late Pleistocene and Holocene. Transitions from humid to arid conditions and vice versa led to rise and shrinkage of lake levels and also affected the connecting drainage networks (Sagri et al., 2008; Carnicelli et al., 2009; Foerster et al., 2012; Junginger and Trauth, 2013; Foerster et al., 2015; Trauth et al., 2019). We propose that the connected drainage systems in our research area, such as the Bisare River, might have reacted to these transitions with changes in their depositional and erosional behaviour. Furthermore, considering the location of our research areas within a region that have been tectonically active since the Plio–Pleistocene, we can assume that the aforementioned extensive surface processes most likely started already during the Late Pleistocene (Fig. 5). However, we propose that due to today's intensified human impact in the form of clearance of the vegetation cover and cropland expansion, leading to higher runoff, obsidian raw material comes more frequently and in higher amounts up to the surface than during prehistoric times.

Archaeological evidence from Mt Damota and Sodicho Rockshelter shows that groups of prehistoric humans seem to have adapted to former climatic and hydrological changes, leading to different environmental conditions, with repeated occupation of the rock shelters at higher elevations under different environmental conditions (Brandt et al., 2012, 2017; Vogelsang and Wendt, 2018). During such periods these groups were probably exploiting these higher elevated areas with the awareness of their sufficient water and food resources, shelter, and the access to obsidian raw material (cf. Vogelsang et al., 2018). Although it is not yet clear which specific obsidian outcrops were used by the prehistoric humans, first results of obsidian microprobe analysis point to the exploitation of raw material from outcrops in the Bisare area by the inhabitants of both rock shelters (Vogelsang, unpublished information, 2019).

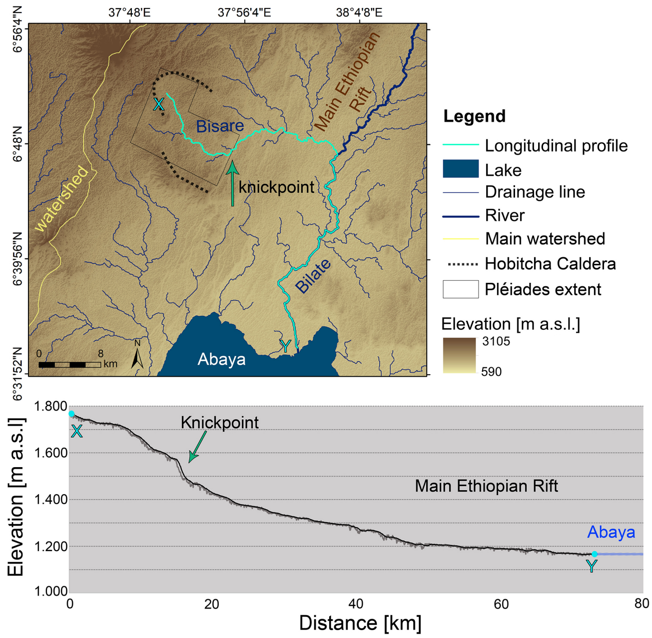

Figure 5. Map showing the calculated drainage networks southeast of the Bisare River catchment that flow into Lake Abaya. Following the longitudinal profile of the Bisare River (green line and graph), a sudden change in slope (knickpoint) at the outflow from the Hobitcha Caldera stands out (DEM data by ASTER GDEM; illustration by Elena Hensel).

6 Conclusions

This study gives an insight into to the potential of a combination of hydrological and geomorphological analyses by applying field surveys, remote sensing, geographical information systems, and radiocarbon dating, as well as investigations of the archaeological site distribution, to reconstruct the interplay between past hydrological conditions and Paleolithic settlement activity in a mountainous area of the southwestern Ethiopian Highlands. With our results, we were able to describe the current landscape dynamics and the actual state of known rock shelters and open-air sites, as well as raw material preservation in the study areas. The preserved evidence for repeated human occupation during the Late Pleistocene and Holocene at Sodicho Rockshelter (Vogelsang, unpublished information, 2015 to 2018) hints that the highlands could have provided a refugium during arid phases such as the Last Glacial Maximum (LGM, $\sim 21 \pm 2$ ka) (Mark and Osmaton, 2008). At Mochena Borago, settlement activities reach back >50 ka. During such periods, the exploitation of different, elevation-bound ecosystems allowed access to a heterogeneous spectrum of faunal and lithic resources for prehistoric humans (Vogelsang and Wendt, 2018). Humid–arid transitions in the past must have led to pronounced erosion and badlands formation. We suggest that there is a relationship between widespread gully erosion, badlands formation, and raw material availability. Currently, the study area is a region with strong recent sediment erosion and simultaneous accumulation in a cascading system. Looking into the future, given strongly increased human impact during the last few decades acting together with the currently very active hydrological system, intensified soil loss will lead to further degradation of the archaeological material. However, the transfer of today's circumstances into prehistoric times is complicated, as we cannot prove that currently active processes, e.g. swamp formation, were also active during the Pleistocene. Furthermore, the research sites are situated in an area close to the Main Ethiopian Rift, i.e. a region with pronounced tectonic activity that also has a significant impact on the regional geomorphodynamics. Therefore, at this stage the results do not allow any distinct statement about the transfer of the modern morphodynamics to ancient times, as we have identified only recent phenomena. This means that the calculated drainage lines show the current state in a very active hydrological system that is influenced by both natural effects and intensive human activity. Nevertheless, in the context of further interdisciplinary research that combines well-resolved archaeological and alluvial chronostratigraphies it will be possible to obtain a better general understanding of the interplay between former settlement activity and paleoenvironmental conditions in the Ethiopian Highlands during the Pleistocene.

Data availability. GIS data sets can be requested from the CRC 806 Database via https://doi.org/10.5880/SFB806.49 (Hensel et al., 2019).

Author contributions. The geomorphological field mapping and drilling were carried out by OBu and OBo. Archaeological survey was conducted by RV. EAH performed GIS-based mapping, geomorphological–hydrological analyses, and preparation of the paper. All co-authors contributed to, read, and approved the paper.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue "Geoarchaeology and past human–environment interactions". It is not associated with a conference.

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Research article

Neolithic settlement dynamics derived from archaeological data and colluvial deposits between the Baar region and the adjacent low mountain ranges, southwest Germany

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Abstract: The present study combines archaeological data with archaeopedological data from colluvial deposits to infer Neolithic settlement dynamics between the Baar region, the Black Forest and the Swabian Jura. A review of the state of archaeological research and an analysis of the processes leading to the discovery of the Neolithic sites and thereby the formation of the current archaeological site distribution in these landscapes is presented. The intensity of land use in the study area is compared with other landscapes in southern Germany using site frequencies. Phases of colluvial deposition are dated using AMS ^{14}C ages of charcoals and luminescence ages of sediments and interpreted as local proxies for a human presence. Archaeological source criticism indicates that the distribution of the Neolithic sites is probably distorted by factors such as superimposition due to erosion and weathering effects limiting the preservation conditions for Neolithic pottery. A reconstruction of Neolithic settlement dynamics is achieved by complementing the archaeological data with phases of colluviation. Evidence for a continuous land use in the Baar region throughout the Neolithic is provided and sporadic phases of land use on the Swabian Jura and in the Black Forest are identified. In the late and final Neolithic, an intensification of colluvial formation can be noticed in the low mountain ranges.

Kurzfassung: In der vorliegenden Studie werden archäologische Daten mit bodenkundlichen Daten aus kolluvialen Ablagerungen verknüpft, um Phasen der Landnutzung während des Neolithikums zu ermitteln und somit neolithische Siedlungsdynamiken zwischen der Baar, dem Schwarzwald und der

Schwäbischen Alb beschreiben zu können. Ausgehend von einer Auswertung der lokalen archäologischen Forschungsgeschichte und einer quellenkritischen Betrachtung des Fundstoffes erfolgt eine Evaluierung der Verbreitung der gegenwärtig bekannten neolithischen Fundstellen. Auf der Basis von Fundstellenfrequenzen wird eine überregionale Einordnung der Intensität der lokalen Siedlungsaktivität vorgenommen. Phasen der Kolluvienbildung werden durch Radiokohlenstoffdatierungen von Holzkohlen und Lumineszenzalter von Sedimenten datiert und als Hinweise auf eine Anwesenheit des Menschen interpretiert. Die quellenkritische Auswertung des Fundstoffes legt den Verdacht nahe, dass die Verbreitung der neolithischen Fundstellen im Arbeitsgebiet durch verschiedene Faktoren beeinflusst wird. Demnach wird die Zugänglichkeit neolithischer Fundstellen durch Über- und Umlagerung aufgrund von Erosion verzerrt und die Erhaltung von Keramik durch lokale Witterungsbedingungen eingeschränkt. Die Beschreibung neolithischer Siedlungsdynamiken gelingt letztlich durch die Korrelation der archäologischen und bodenkundlichen Daten. Für den gesamten Verlauf des Neolithikums lässt sich auf diese Weise eine neolithische Besiedlung der Baar aufzeigen. Im Schwarzwald und auf der Schwäbischen Alb lassen sich hingegen nur sporadische Landnutzungsphasen aufzeigen. Im Spät- und Endneolithikum lässt sich in den Mittelgebirgen eine Verstärkung der Kolluvienbildung beobachten.

1 Introduction

The transition from a mobile subsistence based on hunting and gathering to sedentary farming communities marks a turning point in human history. As this shift had far-reaching consequences for the further development of societies, it is often referred to as the "Neolithic Revolution" (Childe, 1936; Teuber et al., 2017). This transition changed not only the human perception of landscapes, but it also had a major impact on the environment (Gerlach, 2003, 2006). The vegetation was affected by local deforestation carried out in order to establish settlements and introduce fields for plant cultivation and for livestock. As soils became an important resource for survival, they needed maintenance with manure and had to be worked with ploughs to ensure sufficient yields (Lüning, 2000). Already in the Early Neolithic, both changes in vegetation and ploughing resulted in the erosion of soils in the vicinity of the settlements (Saile, 1993; Semmel, 1995). The correlate sediments of soil erosion caused by human activities are called colluvial deposits and can be seen as pedosedimentary archives of human activities in the landscape (Leopold and Völkel, 2007; Kadereit et al., 2010; Kühn et al., 2017). Because they are proxies for land use, they can be used to study pre- and early historic human–environment interactions (Dotterweich, 2008; Fuchs et al., 2011; Pietsch and Kühn, 2017; Voigt, 2014). Colluvial deposits always represent the adjacent upward slope areas and therefore provide local "site biographies" with a high resolution (Henkner et al., 2017, 2018a, c).

So far, colluvial deposits have been used mainly to investigate the long-term consequences of pre- and early historic agriculture in the lowlands in southwestern Germany. Prehistoric land use in low mountain ranges has rarely been investigated using archaeopedological methods (Fuchs et al., 2011; Ahlrichs, 2017; Henkner et al., 2018a, c). Especially in these landscapes, pedological datasets from colluvial deposits are an important supplement to archaeological data. Low mountain ranges such as the Black Forest in southwestern Germany are often densely forested and cannot be adequately investigated solely by using archaeological methods. As a consequence, the kind and intensity of prehistoric land use in this landscape has been a matter of speculation for decades (Lais, 1937; Valde-Nowak, 2002). Due to the climate, relief and soils, the agricultural potential of the Black Forest is fairly limited in comparison to adjacent lowlands, where fertile soils on loess are abundant (Gradmann, 1931, 1948). Therefore, it has been suspected for a long time that this unfavourable landscape was basically avoided in prehistoric times and not colonized before the High Middle Ages (e.g. Schreg, 2014; Ahlrichs, 2017).

However, research from recent decades has provided increasing evidence for early phases of land use dating back to the Neolithic (Frenzel, 1997; Valde-Nowak, 1999; Rösch, 2009). Consequently, the archaeological and archaeobotanical research from the last three decades opens the demand for a reassessment of the relationship between favourable and unfavourable landscapes in the Neolithic. Currently, an interdisciplinary research project at the University of Tübingen takes up this issue using methods from prehistoric archaeology and soil science. The research presented in this paper focuses on the following objectives:

- evaluation of the archaeological data and an identification of factors that influenced the current distribution of the Neolithic sites
- discussion of Neolithic settlement dynamics between the Baar region, the Black Forest and the Swabian Jura with a high spatial and chronological resolution by synchronizing archaeological and pedological data.

2 Regional setting

The study area is located northwest of Lake Constance in the federal state of Baden-Württemberg, southwestern Germany. Geographically, it includes three landscapes: the southeastern part of the central Black Forest, the Baar region and the southwestern part of the Swabian Jura (Fig. 1). The topography changes significantly between these landscapes (Gradmann, 1931; Reichelt, 1977; Schröder, 2001). Deeply cut valleys with steep slopes characterize the Black Forest with an elevation of up to 1100 m a.s.l., while the southwestern part of the Swabian Jura consists of several high plateaus such as the Heuberg and Lindenberg with elevations up to 1000 m a.s.l., separated by wide river valleys. The Baar region, however, is an elevated basin-shaped landscape (German: *Hochmulde*) with an average elevation of 600–800 m a.s.l. and gentle rolling slopes. In contrast to the Baar region, the two low mountain ranges represent agriculturally unfavourable regions with an oceanic climate (Reichelt, 1977; Tanha, 1986). This is due to high amounts of annual precipitation between 1000 and 1900 mm, low average temperatures ranging from 4 to 6 °C as well as long periods of winter and frost (Gradmann, 1931; Knoch, 1953). The climate in the Baar region is more continental with an average annual temperature of 7–8 °C and an average precipitation of 850 mm per year (Siegmund, 1999, 2006). In addition, the landscapes can be differentiated with regard to their pedology (Kösel and Rilling, 2002; Lazar, 2005; Lazar and Rilling, 2006). Due to fertile soils on loess, the local population used to describe the Baar region as the breadbasket of Baden (Reich, 1859; Deecke, 1921). This is in contrast to the Black Forest, where low-yielding and acidic soils limit the agricultural potential. The Swabian Jura is characterized by a karst landscape with low-yielding soils as well.

3 Methods

3.1 Assessment of archaeological site distributions

In order to study the pre- and early historic settlement dynamics in this regional setting, an archaeological database was set up in 2014. In total, we recorded 1826 archaeological sites using local area files (German: *Ortsakten*) from the State Office for Cultural Heritage Baden-Württemberg. The sites date from the late Upper Palaeolithic to the end of the 12th century CE (Ahlrichs et al., 2016; Ahlrichs, 2017). The database includes 107 sites that can be used for a discussion of Neolithic land use and settlement dynamics. In large study areas like this, changes in settlement patterns can be described and investigated by comparing distribution maps with different time frames (Schier, 1990; Saile, 1998; Pankau, 2007). However, as suggested by Sommer (1991), Gerhard (2006) and Eggert (2012), it is necessary to examine the archaeological data in detail in order to evaluate distribution patterns and thus to provide a reliable analysis of settlement dynamics.

3.1.1 State of local research

First of all, it is necessary to discuss the genesis of the archaeological record. This includes a literature review with respect to the local history of archaeological research. Within this framework, the general nature of the available data will be presented with focus on geographical as well as chronological aspects. To visualize changes in settlement patterns in a geographic information system (GIS), we digitized the position (EPSG: 31 467) of each recorded site if it could be located within a radius of ±250 m based on recent map information. The detection of settlement dynamics requires an accurate dating for the sites of interest with a chronological resolution as high as possible. Therefore, for each recorded site, the available literature was screened for information regarding its chronological position. We distinguished four degrees of chronological precision: epoch, period, phase and sub-phase (Eggert, 2012; Eggert and Samida, 2013).

3.1.2 Intentionality of site discoveries

In addition, quantitative analyses of the circumstances leading to the discovery of the recorded Neolithic sites are necessary. It is crucial to distinguish intentional discoveries from accidental ones (Wilbertz, 1982; Schier, 1990; Pankau, 2007). Intentional discoveries can be the result of field surveys, aerial photography, analysis of airborne light detection and ranging (lidar) data, research excavations, rescue excavations and small prospections. On the other hand, archaeological sites can be discovered accidentally in the course of construction measures, agricultural and forestry activities, land consolidation (German: *Flurbereinigung*), the extraction of raw materials, or randomly when people go for a walk or go hiking. Finally, historical records mentioning prehistoric sites are also included in this category as well as sites that were already known for a long time by local residents before archaeologists discovered their significance – this applies especially to easily accessible structures such as (burial) mounds, ditches or remnants of walls. For a better assessment of the data for the Neolithic, the interpretation of the analyses will also consider the data for the Bronze Age and the pre-Roman Iron Age.

3.1.3 Depth of sites

In addition, the depth of a site in relation to the modern surface can be inferred from the circumstances of its discovery (Schier, 1990; Saile, 1998). They can be grouped in a way which allows a differentiation between sites discovered below, close to or on the modern surface (see Table 2). This analysis takes the data for the Bronze Age and the pre-Roman Iron Age into account as well.

3.1.4 Site distribution in relation to modern land use

Furthermore, modern land use strategies have an impact on the conservation and visibility of prehistoric sites (Schiffer, 1987; Sommer, 1991). Therefore, an analysis of site distributions against the background of different land use types is recommended (Pankau, 2007; Ahlrichs, 2017). For a study of this kind, we use CORINE Land Cover data, provided by the European Environment Agency (EEA) (European Environment Agency, 2007). This raster dataset with a resolution of 100 m contains 44 types of modern land use classes. However, for archaeological purposes, it is appropriate to aggregate these classes to seven main types: urban areas, forests, arable land, grassland, water bodies, bogs or swamps, and landfills or dumpsites (Ahlrichs, 2017). In order to assess whether certain types of land use may lead to distortions in the distribution of prehistoric sites, we use the χ^2 test (Shennan, 1988).

3.1.5 Weathering effects on pottery, stone and coins

The local topography has an influence on the preservation and accessibility of archaeological sites. At certain relief positions, such as upper slopes or crests, artefacts are exposed to weathering for longer time periods and thus have worse conservation conditions than artefacts on foot slopes or in valleys, where they are covered (and thus protected) by sediment due to erosion (Pasda, 1994, 1998; Saile, 2002). Another important factor is the material the artefacts are made of, i.e. pottery, is less resistant to weathering than stone or metal (Geilmann and Spang, 1958; Schiffer, 1987). Therefore, we defined three groups: pottery, stone artefacts and coins. We used artefacts from settlement contexts and single finds dating to “prehistory”, the Palaeo-, Meso- and Neolithic, the Bronze Age, the pre-Roman Iron Age and the Roman Empire (Table 4). We deliberately excluded artefacts from graves because they are directly buried after deposition and less exposed to weathering. In order to establish whether the local topography does indeed influence the preservation of prehistoric artefacts, we analysed the distribution of the three material groups using a non-dimensional unit called morphometric protection index (MPI) from Yokoyama et al. (2002) in the System for Automated Geoscientific Analyses (SAGA) geographic information system (GIS) (Conrad et al., 2015). This analysis is based on a revised and error-corrected version of a digital elevation model (DEM) with a resolution of 90 m derived from the Shuttle Radar Topography Mission (SRTM) carried out by the National Aeronautics and Space Administration (NASA) (Jarvis et al., 2008). However, due to the chronological composition of the three material groups, this analysis provides only general information regarding the effect of weathering due to topographic openness. Because of the small number of Neolithic sites in this study area, it is not possible to perform such an analysis only for the Neolithic.

3.1.6 Local site frequencies in relation to other study areas

The local site frequency (German: *Fundstellenfrequenz*) is determined and compared with other regions in southern Germany (Fig. 6) in order to evaluate local changes in demography and settlement intensity. This statistical value indicates how many sites came into existence in the course of a century and thus represents an indicator of the intensity of settlement. The site frequency is calculated by multiplying the number of archaeological sites of a period by 100 and then dividing it by the duration of the period in years (Saile, 1998; Schefzik, 2001; Pankau, 2007).

3.2 Investigation of colluvial deposits

3.2.1 Field methods

The archaeological database was used to select 13 locations for the investigation of colluvial deposits in the study area (Fig. 1). In the Black Forest, colluvial deposits were investigated at the spring sources of the Breg and the Brigach rivers as well as at Bubenbach and Lehmgrubenhof. In the Baar region, colluvial deposits were studied at Magdalenenberg, Grüningen, Fürstenberg, Geisingen and Spaichingen. Phases of colluvial deposition were studied on the Lindenberg and the Heuberg (Böttingen, Königsheim and Rußberg). Humans can force phases of colluviation through a variety of activities affecting the vegetation, such as grazing and farming, deforestation, mining, building settlements, ramparts or other infrastructures (Starkel, 1987; Leopold and Völkel, 2007). However, it is difficult to conclude directly from a colluvial deposit the activities leading to its formation. In general, colluvial deposits lacking archaeological finds are more likely to be the result of agricultural activities or deforestation than of settlement activities. Colluvial deposits containing scattered archaeological finds qualify as relocated material from a settlement located in the catchment area of the colluvial deposit (Wunderlich, 2000; Niller, 1998). It is possible to correlate phases of colluviation with archaeological data because the deposits can be dated as well (Ahlrichs et al., 2016; Ahlrichs, 2017; Henkner et al., 2017, 2018a, c).

In total, 68 soil profiles were described between 2013 and 2015 in the field (Henkner et al., 2018a) according to the German soil classification system (Ad-hoc-AG Boden, 2005), the Food and Agriculture Organization of the United Nations (FAO, 2006) as well as the world reference base for soil resources (IUSS Working Group WRB, 2015). A main characteristic for anthropogenic colluvial deposits is a lack of autochthonous pedogenic properties; hence their horizons are designated M (M = Latin *Migrare*, to migrate) in the German soil classification system. In our studies, we use the M horizon together with the FAO nomenclature in order to distinguish between colluvial horizons and others with different pedogenic development (Henkner et al., 2017, 2018a, c). To understand the local stratigraphy of colluvial deposits at each

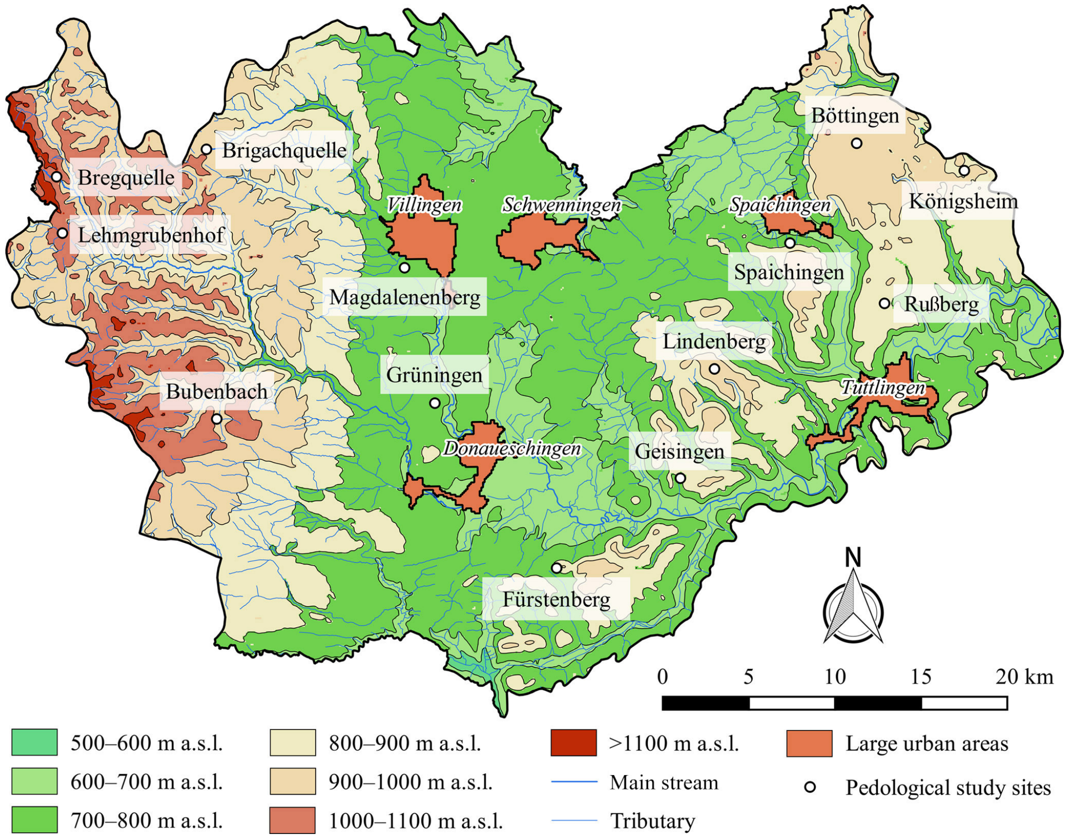

Figure 1. Study area and sites of investigated colluvial deposits. The topography is based on a digital elevation model provided by NASA (Jarvis et al., 2008). The mapping of rivers is based on Amtliches Digitales Wasserwirtschaftliches Gewässernetz (AWGN) provided by Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW).

site, we used catenas, i.e. a sequence of soil profiles extending from the upper slope to foot slope positions, thus covering differences in topography, elevation and drainage as well as erosion or deposition. Samples for dating phases of colluvial deposition were taken from profiles regarded as the most characteristic for a site due to their detailed pedostratigraphy (Henkner et al., 2017, 2018a, c).

3.2.2 Laboratory methods

All soil chemical analyses were done in the Laboratory of Soil Science and Geoecology at the University of Tübingen. Total C and N contents (mass %) were analysed using oxidative heat combustion at 1150 °C in a He atmosphere (element analyser "vario EL III", Elementar Analysensysteme GmbH, Germany, in CNS mode). Soil organic C content (SOC) was determined using $SOC = C_{total} - CaCO_3 \times 0.1200428$, and soil organic matter (SOM) was calculated using the factor 1.72 (Ad-hoc-AG Boden, 2005; Eberhardt et al., 2013; Henkner et al., 2018c).

To estimate the deposition ages of colluviation, we used two methods: charcoal samples were taken for radiocarbon dating by means of accelerator mass spectrometry (AMS). The samples were processed in the ^{14}C laboratories in Jena, Mannheim, Erlangen and Poznań. When interpreting AMS ^{14}C from colluvial deposits, it has to be taken into account that the ages represent the point in time at which the carbon exchange between the wood and the biosphere broke off, i.e. the year in which the sampled tree ring was formed (Taylor and Bar-Yosef, 2014). This age does not necessarily coincide with the time when the charcoal was formed. Subsequently, the AMS ^{14}C dates usually represent the maximum age of the colluvial deposition from which they were taken (Ahlrichs et al., 2016; Henkner et al., 2017). The calibration of the data was done with OxCal 4.2 and the calibration curve IntCal13 (Bronk Ramsey, 2009; Reimer et al., 2013).

Furthermore, optical stimulated luminescence (OSL) dating was applied, using opaque steel cylinders with a diameter of 4.5 cm for sampling. For equivalent dose (De) determinations, the coarse-grain (90–200 µm) quartz fraction was prepared and measured with a single-aliquot regenerative-dose (SAR) protocol after Murray and Wintle (2000). All luminescence measurements were carried out at the luminescence laboratory of the Justus Liebig University in Giessen, using a Freiberg Instruments Lexsyg reader (Lomax et al., 2014). For data analysis, the R luminescence package (Kreutzer et al.,

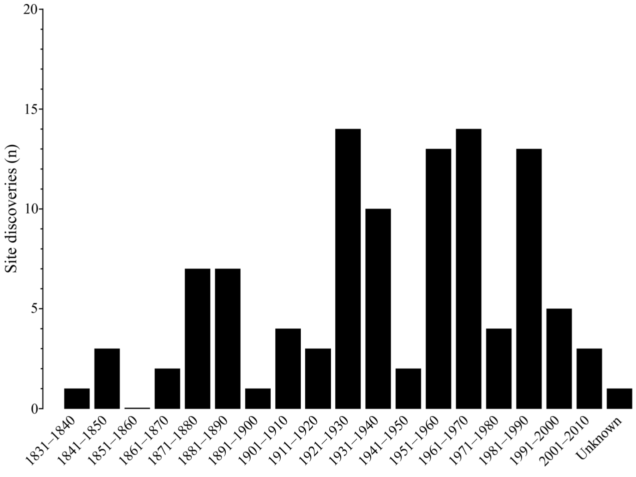

Figure 2. Distribution of Neolithic site discoveries.

2016) was used. In contrast to radiocarbon dating, OSL is assumed to date the time of colluvial deposition because it determines the period of time when the sampled sediment was last exposed to sunlight. Postsedimentary reworking (e.g. by bioturbation), however, should generally not be neglected when luminescence ages are interpreted as ages of colluvial deposition (see Reimann et al., 2017). A prerequisite for the successful application of this method is that the sampled sediments were sufficiently exposed to sunlight during their relocation. In case of insufficient daylight exposure, OSL dating would result in an age overestimation (Bußmann, 2014; Henkner et al., 2018a). Nevertheless, colluvial deposits can generally be dated successfully by OSL as demonstrated in numerous studies from various landscapes and cultural periods (Fuchs and Lang, 2009; Kadereit et al., 2010).

4 Results

4.1 Archaeological data

4.1.1 State of local research

Since the mid-thirties of the 19th century, Neolithic sites have been known in the study area (Fig. 2). Several decades later, Wagner (1908), Haug and Sixt (1914) published the first comprehensive archaeological catalogues which included these early discovered sites. From the 1920s onwards until the 1950s, Paul Revellio led the archaeological research in the Baar region (Hall, 1968). He carried out rescue excavations at construction sites as well as field surveys and small prospections. Revellio recorded and published most of the Neolithic sites discovered during these three decades (Revellio, 1924, 1932 and 1938). In the 1930s, Fischer (1936) and Stoll (1941 and 1942) also studied the Neolithic settlement dynamics in the region. When Revellio retired in the 1950s, Rudolf Ströbel continued his work (Benzing, 1974). After his death, Spindler (1977) and Schmid (1991 and 1992) were the only researchers who provided analyses of the Neolithic sites discovered since the 1960s. In addition, few Neolithic sites were discussed in studies with a supra-regional focus (Paret, 1961; Itten, 1970; Pape, 1978). In general, it has to be noted that very few Neolithic sites in the study area have been investigated in the field (for exceptions see Wagner, 2014; Seidel, 2015). The vast majority were merely registered and published in the form of short site reports (see Schmid, 1992; Ahlrichs, 2017). In this context, it is noteworthy that in the course of the 20th century, several researchers carried out field surveys in the Baar region and adjacent landscapes. Although the surveyed territories cover a large part of the study area (Fig. 3), only one Neolithic site was actually discovered in the course of these surveys (Ahlrichs, 2017).

Against the background of this research history, we recorded 107 archaeological sites dating to the Neolithic. Based on the available data in the local area files and the literature we were able to assign a point coordinate to 75 sites (Fig. 7). In the remaining 32 cases this was not possible due to a lack of geographical information. Furthermore, after a review of the sites with regard to their archaeological dating, we were able to assign 49 sites to different Neolithic periods. Due to the nature of the artefacts, it was not possible to date the Neolithic sites on the level of phases or even sub-phases. The remaining 58 sites date to the "Neolithic" in general because the artefacts recovered at these sites are too fragmented or atypical for any further chronological specification. Therefore, more than half of the recorded sites are not suitable for the description of local-settlement dynamics. These results mirror the state of archaeological research of the individual sites: out of 107 registered Neolithic sites, no more than 12 sites were studied in the course of research excavations. Out of those 12 sites, 9 had to be excavated because they were discovered during excavations of archaeological sites dating to later periods. Furthermore, rescue excavations took place at four Neolithic sites after their initial discovery. This unbalanced ratio between excavated and not excavated sites has been observed in other study areas too (Schmotz, 1989). With respect to the state of research in the Baar region and adjacent landscapes, 20 sites qualify as settlements due to the presence of grinding stones and/or features such as pits or postholes. At five sites, human remains were recovered, classifying these locations as burial sites. The remaining 82 sites are composed of single finds or small artefact assemblages that currently do not allow a more detailed description of the activities that took place at these sites (Ahlrichs, 2017).

4.1.2 Intentionality of site discoveries

In contrast to the Bronze Age and the pre-Roman Iron Age, an extraordinarily large number of Neolithic sites were discovered accidentally (Table 1). In total, 87 out of 107 sites are associated with non-intentional modes of discovery. Most of them were found randomly ($n = 38$) during agricultural and forestry activities ($n = 18$) or in the course of construc-

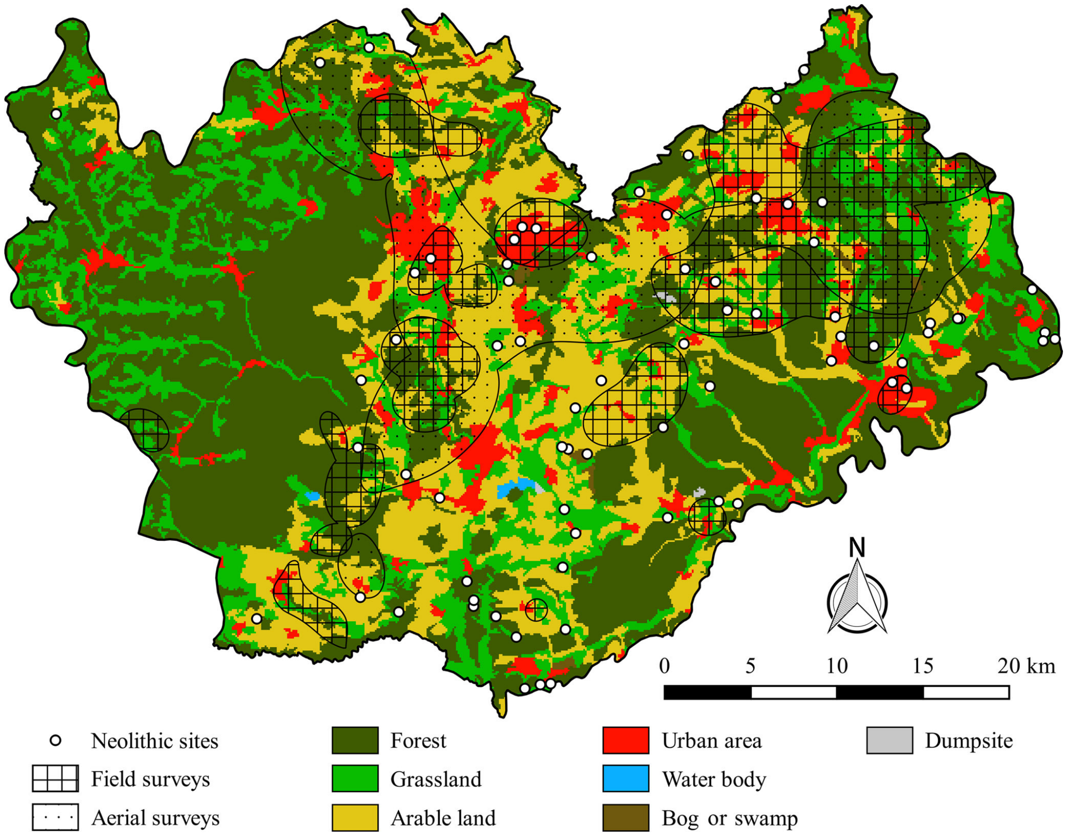

Figure 3. Modern land use according to CORINE Land Cover data (European Environment Agency, 2007) and areas studied by field surveys (Ahlrichs, 2017).

Table 1. Intentionality of archaeological site discoveries.

Intentionality	Modes of discovery	Neolithic		Bronze Age		Pre-Roman Iron Age	
		(*n*)	(%)	(*n*)	(%)	(*n*)	(%)
Non-intentional	Long known	1	1	3	2	17	8.5
	Random discovery	38	35.5	22	16	28	14
	Working measure	16	15	48	34	47	23.5
	Land consolidation	1	1	1	1	2	1
	Extraction of raw materials	8	7.5	6	4	3	1.5
	Historical records	0	0	0	0	0	0
	Agricultural and forestry activities	18	17	10	7	8	4
Intentional	Field survey	1	1	18	13	47	23.5
	Lidar data	0	0	0	0	0	0
	Aerial photography	0	0	0	0	3	1.5
	Research excavation	9	8	8	6	7	3.5
	Rescue excavation	0	0	0	0	2	1
	Prospection	0	0	0	0	1	0.5
Unknown	Unknown	15	14	24	17	35	17.5
	Sum	107	100	140	100	200	100

tion measures ($n = 16$). Less than 10 % of the Neolithic sites are associated with intentional modes of discovery. These include the nine Neolithic sites mentioned earlier that were registered during excavations of archaeological sites dating to later periods and a single site that was discovered in a field survey. These results are even more indicative of potential gaps in the distribution of the sites when compared to younger epochs. The numbers of intentionally discovered sites are approximately 19 % for the Bronze Age and 30 % for the pre-Roman Iron Age. Altogether, 18 Bronze Age sites and 47 sites dating to the pre-Roman Iron Age were registered during field surveys (Table 1). This indicates that the material remains from these epochs may be more resistant to weathering compared to the ones dating to the Neolithic. In addition, the numerous discoveries during field surveys can be used to correct potential distortions in the Bronze Age and Iron Age site distributions caused by construction sites in urban areas. However, there is no such balance for the Neolithic sites.

4.1.3 Depth of sites

In total, 40 Neolithic sites were discovered on the modern surface, 19 were just slightly below the surface and about another 33 below the surface (Table 2). Initially, these results are quite similar with those for the Bronze Age and the pre-Roman Iron Age. However, a closer look at the archaeological data shows that at just one site Neolithic pottery was found on the recent surface. Overall, at 37 out of 38 sites discovered on the surface the artefacts were made of stone, which is far more resistant to weathering. This is in contrast to the Bronze Age and the pre-Roman Iron Age (Table 2). In total, 43 Bronze Age sites were discovered on the modern surface and at 27 of them pottery was present. In the case of the pre-Roman Iron Age, 92 sites were registered on the modern surface; pottery was found at 60 of them (Ahlrichs, 2017). These results suggest that Neolithic pottery may be less resistant to weathering on the surface than pottery from the Bronze Age and the pre-Roman Iron Age. Consequently, a distortion in the distribution of Neolithic sites is possible, as a preservation of pottery is more likely at topographic positions where it is superimposed shortly after its deposition.

4.1.4 Site distribution in relation to modern land use

On arable land, grassland as well as in bogs and at dumpsites about as many Neolithic sites were registered as would be expected with an even distribution over the land use classes (Fig. 3, Table 3). Consequently, these land use classes do not have much influence on the distribution of the sites. In contrast, urban areas and forests seem to have an influence on the distribution of Neolithic sites. In urban areas, the number of registered sites exceed the number of expected sites. This result can be attributed to the fact that construction measures are more likely to occur in settlements than in the other land use classes. As the frequency of construction measures increases, so does the probability of discovering new sites. This can lead to artificial clusters of prehistoric sites in urban areas (Schier, 1990; Gerhard, 2006). As Fig. 3 indicates, this does not apply to the Neolithic sites in this study area, since none of the modern settlements correlates with a remarkably large number of Neolithic sites. However, it is noticeable that several sites in the valleys of the Swabian Jura were discovered during construction measures. It has been suggested in earlier research that the density of prehistoric sites in the valleys of the Swabian Jura is low because their archaeological visibility and accessibility are reduced due to erosion (Paret, 1961; Wahle, 1973). This seems to apply to our study area as well. In addition, the visibility of prehistoric sites is limited by dense vegetation in areas covered by forests. As a result, fewer Neolithic sites were registered in forests than expected. This is a crucial factor in understanding the absence of Neolithic sites in Black Forest and in large parts of the Swabian Jura (Lais, 1937; Valde-Nowak, 2002; Pankau, 2007).

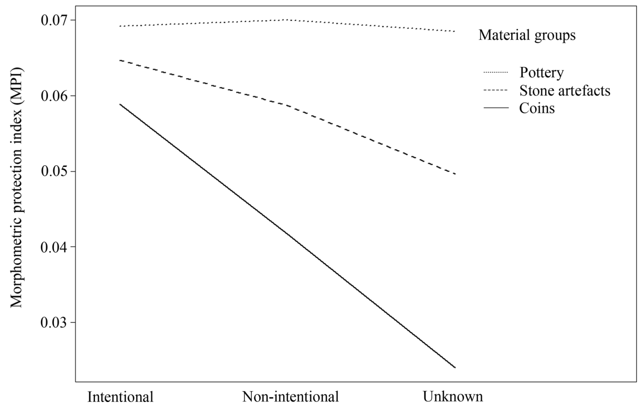

Figure 4. Comparison of average MPI values for pottery, stone artefacts and coins with regard to the intentionality of the site discoveries

4.1.5 Weathering effects on pottery, stone and coins

Each of the three material groups shows a specific frequency distribution over the morphometric protection index (MPI). In fact, pottery and coins can be differentiated due to their distinct trends (Table 5). As can be seen in Fig. 5, pre- and early historic pottery has often been registered in topographical positions with a high MPI such as foot slopes or valleys. In contrast, the frequency distribution of coins concentrates in topographic areas with a fairly small MPI, while stone artefacts take an intermediate position between these groups. Compared to pottery, however, there is also a trend towards areas with small MPIs for stone artefacts (Fig. 5). Since these trends might have been influenced by the circumstances leading to the discovery of the sites, an additional analysis was carried out taking into account the intentionality of the site discoveries. Figure 4 shows the average MPI values of the

Table 2. Relation of archaeological sites to the modern surface.

Relation to surface	Modes of discovery	Neolithic		Bronze Age		Pre-Roman Iron Age	
		(*n*)	(%)	(*n*)	(%)	(*n*)	(%)
Above surface	Field survey	1	0.93	18	12.86	47	23.5
	Random discovery	38	35.51	22	15.71	28	14
	Long known	1	0.93	3	2.14	17	8.5
	Historical records	0	0	0	0	0	0
Close to surface	Agricultural or forestry activities	18	16.82	10	7.14	8	4
	Lidar data	0	0	0	0	0	0
	Aerial photo	0	0	0	0	3	1.5
	Land consolidation	1	0.93	1	0.71	2	1
Below surface	Working measure	16	14.95	48	34.3	47	23.5
	Research excavation	9	8.41	8	5.71	7	3.5
	Rescue excavation	0	0	0	0	2	1
	Prospection	0	0	0	0	1	0.5
	Extraction of raw materials	8	7.5	6	4.29	3	1.5
Unknown	Unknown	15	14.02	24	17.14	35	17.5
	Sum	107	100	140	100	200	100

Table 3. Distribution of Neolithic sites over modern land use.

Land use	Spatial abundance (%)	Recorded sites (*n*)	Expected sites (*n*)	χ^2 value
Water bodies	0.1	0	0.08	0.08
Urban areas	7.88	16	5.91	17.23
Arable land	24.43	22	18.32	0.74
Grassland	20.16	15	15.12	0
Forest	47.1	22	35.33	5.03
Bogs or swamps	0.25	0	0.19	0.19
Dumpsites or landfills	0.08	0	0.06	0.06
Sum	100	75	75	23.33

The critical χ^2 value for 6 degrees of freedom is at 22.46 (significance level: 0.001 %).
In this case, the site distribution is highly significantly unequal (see Ihm et al., 1978, p. 595).

intentional and non-intentional site discoveries for each material group. The results demonstrate that pottery was registered in topographic positions with a very specific MPI, regardless of whether they were recorded in the course of intentional or non-intentional modes of discovery. This cannot be seen in the other groups. These results suggest that the topography has an influence on the preservation and accessibility of pre- and early historic pottery and thus constitutes a crucial factor with respect to the understanding of site distributions in the study area.

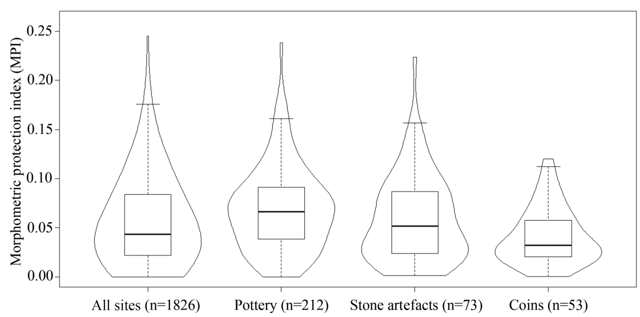

Figure 5. General comparison of average MPI values for pottery, stone artefacts and coins (see also Table 5).

4.1.6 Local site frequencies in relation to other study areas

According to the available archaeological data, the Neolithic settlement of the Baar region and adjacent landscapes are characterized by extremely low site frequencies (Table 6).

Table 4. Distribution of material groups over different epochs and types of archaeological sites.

Epoch	Type of site	Pottery	Stone artefacts	Coins	Sum
"Prehistory"	Settlement	18	1	0	19
	Single finds	1	0	0	1
Palaeolithic	Settlement	0	0	0	0
	Single finds	0	2	0	2
Mesolithic	Settlement	0	1	0	1
	Single finds	0	3	0	3
Neolithic	Settlement	9	10	0	19
	Single finds	1	47	0	48
Bronze Age	Settlement	50	2	0	52
	Single finds	6	2	0	8
Pre-Roman Iron Age	Settlement	94	3	0	97
	Single finds	5	0	6	11
Roman Empire	Settlement	15	1	12	28
	Single finds	13	1	35	49
Sum		212	73	53	338

Table 5. Comparison of average MPI values for pottery, stone artefacts and coins (see also Fig. 5).

Material group	Minimum	First quartile	Median	Mean	Second quartile	Maximum	Standard deviation
All sites ($n = 1826$)	0	0.0217	0.0431	0.0557	0.0839	0.245	0.0429
Pottery ($n = 212$)	0	0.0388	0.066	0.069	0.091	0.2381	0.0436
Stone artefacts ($n = 73$)	0.0012	0.024	0.0515	0.0588	0.0866	0.2236	0.0435
Coins ($n = 53$)	0.0003	0.0204	0.032	0.0416	0.0573	0.1198	0.0283

The Early Neolithic and the Final Neolithic are the only periods for which we could calculate site frequencies of one and nearly two sites per hundred years. The other Neolithic periods are characterized by even smaller site frequencies. In fact, similar results cannot be observed in any other study area in southern Germany (Table 6, Fig. 6). On the contrary, in landscapes such as the Wetterau or Maindreieck, frequencies of up to 30 sites per century can be demonstrated. The Brenz–Kocher Valley on the Swabian Jura is the only landscape with similarly low site frequencies. In general, it can be assumed that the calculated site frequencies do reflect regional trends in Neolithic settlement dynamics, even though the results may be affected to a certain degree by local research traditions. Altogether, we assume that the Neolithic settlement density must have been very low in the study area. This probably results from the limited accessibility of Neolithic sites as well as poor conditions for the conservation of pottery due to the topography and modern land use.

4.2 Colluvial deposits

4.2.1 Archaeopedological dataset

The entire dataset includes 93 AMS ^{14}C datings of charcoals, 47 luminescence datings of colluvial deposits and laboratory results of 728 bulk soil samples (Henkner et al., 2018b). Since this paper deals with the Neolithic land use, this section will focus on those 21 AMS ^{14}C ages (Table 7) and 9 luminescence ages (Table 8) associated with the Neolithic. In the following, the results for each of the three landscapes are presented.

4.2.2 The Baar region

At the beginning of the Neolithic, phases of land use triggered colluvial formation at Magdalenenberg and Fürstenberg. A luminescence age from Mag1_14 (GI0132) and a radiocarbon age from Fue9 (Erl-20278) date the related colluvial deposits into the Early Neolithic period. This is supplemented by three OSL samples covering the entire time frame from the early to the Younger Neolithic due large standard errors (GI0183, GI0184, GI0248). There are few sam-

Table 6. Supra-regional comparison of Neolithic site frequencies (see also Fig. 6).

Region	Early Neolithic	Middle Neolithic	Younger Neolithic	Late Neolithic	Final Neolithic	Reference
Baar	1.2	0.83	0.11	0.86	1.85	This study
Brenz–Kocher Valley	5	1.5	2.33	–	1.23	Pankau (2007)
Estuary of the Isar river	5.2	13.5	3.22	–	3.54	Schmotz (1997, 2001)
Northwestern Maindreieck	11.8	2.33	4.33	–	5.08	Obst (2012)
Groß-Gerau	11.8	20.83	5	–	10.62	Gebhard (2007)
Danube Valley near Regensburg	13.4	20.5	3.89	–	6.46	Schier (1985)
Ries	17.6	6	5.56	–	1.23	Krippner (1995)
Maindreieck	28	30	5.67	5	12.46	Schier (1990)
Wetterau	29.8	15.83	7.22	–	–	Saile (1998)

Table 7. Neolithic AMS ^{14}C radiocarbon dates from charcoals in colluvial deposits from Fürstenberg (Fue), Magdalenenberg (Mag), Spaichingen (Spa), Geisingen (Gei), Grüningen (Gru), Lehmgrubenhof (Leh), Brigach spring (Bri), Königsheim (Koe), Lindenberg (Lin) and Böttingen (Boe). The data calibrations were done with OxCal 4.2 and the calibration curve IntCal13 (Bronk Ramsey, 2009; Reimer et al., 2013).

Lab code	Landscape	Site	Profile	Depth (cm)	Horizon	BP ($a \pm$ error)	cal BCE or CE (1σ)	cal BCE or CE (2σ)	Neolithic period(s)
Erl-20278	Baar	Fue	9	135	M4	6526 ± 66	cal BCE 5560–5380	cal BCE 5620–5360	Early Neolithic
Poz-36954	Baar	Mag	1_10	65	M2	4970 ± 40	cal BCE 3800–3690	cal BCE 3930–3650	Younger Neolithic
Erl-20132	Baar	Mag	1_14	75	2 M4	5071 ± 51	cal BCE 3950–3800	cal BCE 3980–3710	Younger Neolithic
P 12878	Baar	Spa	1	185	2 MBl	5040 ± 18	cal BCE 3950–3780	cal BCE 3960–3710	Younger Neolithic
Erl-20276	Baar	Fue	9	90	M2	4557 ± 67	cal BCE 3490–3100	cal BCE 3520–3020	Late Neolithic
Erl-20277	Baar	Fue	9	115	M3	4477 ± 58	cal BCE 3340–3030	cal BCE 3360–2930	Late Neolithic
P 14445	Baar	Gei	2	137	5 BgM3	4278 ± 14	cal BCE 2910–2880	cal BCE 2920–2880	Late Neolithic
P 13418	Baar	Gei	2	144	3 MBg	4070 ± 26	cal BCE 2840–2490	cal BCE 2860–2480	Final Neolithic
Erl-20137	Baar	Gru	8_14	105	2 M3	3889 ± 40	cal BCE 2470–2300	cal BCE 2480–2210	Final Neolithic
Erl-20275	Baar	Fue	9	60–70	M1	3918 ± 61	cal BCE 2480–2290	cal BCE 2580–2200	Final Neolithic
P 12871	Black Forest	Leh	3	58	2 M3	5354 ± 55	cal BCE 4330–4050	cal BCE 4440–3960	Younger Neolithic
P 12865	Black Forest	Bri	1	111	4 BgM2	4394 ± 63	cal BCE 3330–2900	cal BCE 3370–2710	Late Neolithic
P 12920	Black Forest	Bri	4	90	M4	3783 ± 14	cal BCE 2280–2140	cal BCE 2290–2140	Final Neolithic
P 12910	Swabian Jura	Koe	3	29	M2	6191 ± 51	cal BCE 5300–5010	cal BCE 5380–4840	Early and middle Neolithic
P 12903	Swabian Jura	Lin	3	80	M5	5685 ± 18	cal BCE 4550–4460	cal BCE 4670–4440	Middle Neolithic
P 12896	Swabian Jura	Lin	2	58	2 M3	5464 ± 45	cal BCE 4450–4230	cal BCE 4470–4050	Younger Neolithic
P 12897	Swabian Jura	Lin	2	90	3 M4	4623 ± 17	cal BCE 3500–3360	cal BCE 3520–3340	Late Neolithic
P 12900	Swabian Jura	Lin	3	43	M2	3937 ± 52	cal BCE 2570–2290	cal BCE 2840–2140	Final Neolithic
P 12907	Swabian Jura	Koe	2	243	M4	4326 ± 51	cal BCE 3270–2870	cal BCE 3340–2670	Late and Final Neolithic
P 12925	Swabian Jura	Lin	2	74	M4	3770 ± 14	cal BCE 2280–2140	cal BCE 2290–2060	Final Neolithic
P 12888	Swabian Jura	Boe	2	32–36	M	3869 ± 49	cal BCE 2470–2210	cal BCE 2570–2060	Final Neolithic

ples dating to the Middle Neolithic. These include the above mentioned OSL samples from Fue8 (GI0183, GI0184) and Fue9 (GI0248) as well as one OSL sample from Mag1_14 (GI0131). The archaeopedological results indicate no significant change in the settlement pattern in the Baar region until the end of the Middle Neolithic. The transition to the Younger Neolithic is marked by a significant increase in radiocarbon ages. In this period, land use continues at Magdalenenberg (Poz-36954, Erl-20132, GI0131) and Fürstenberg (GI0183, GI0184, GI0247, GI0248). Furthermore, an AMS ^{14}C age from Spaichingen (P 1278) dates into this period, thus suggesting local settlement dynamics that went along with the human impact on the eastern Baar. For the Late Neolithic, a distinctive human influence can be demonstrated in several soil profiles. While there are no more indications of land use at Spaichingen and Magdalenenberg, a continuation of land use can be seen in soil profiles at Fürstenberg (GI0247, Erl-20276, Erl-20277). An additional phase of colluviation was detected at Geisingen (P 14445) in the southeastern Baar region. These results indicate both an intensification of land use in the southern Baar region but also point to the cultural significance of the Danube Valley for the Late Neolithic farming societies as an important geographical element with respect to traffic and communication. This is also indicated by imported objects such as an axe made of jadeite found at the Fürstenberg and a hatchet made of copper discovered in the Danube Valley (Wagner, 2014; Seidel, 2015; Ahlrichs, 2017). For the Final Neolithic,

Table 8. Neolithic luminescence ages of sediments from colluvial deposits at Magdalenenberg (Mag), Fürstenberg (Fue), Grüningen (Gru) and Lehmgrubenhof (Leh). Age refers to the year of dating rounded to 2010.

Lab code	Landscape	Site	Profile	Horizon	Depth	Model	De (Gyr)	Age (ka)	cal BCE or CE	Neolithic period(s)
GI0132	Baar	Mag	1_14	M2	69	Central age model	30.5 ± 1.5	8.2 ± 0.8	BCE 6990–5390	Early Neolithic
GI0183	Baar	Fue	8	M5	135	Bootstrap minimum age model 3	20.1 ± 0.9	6.9 ± 0.6	BCE 5490–4290	Early, Middle and Younger Neolithic
GI0184	Baar	Fue	8	M6	162	Bootstrap minimum age model 3	22.3 ± 0.7	6.5 ± 0.7	BCE 5190–3790	Early, Middle and Younger Neolithic
GI0248	Baar	Fue	9	M6	155	Central age model	21.35 ± 0.96	6.61 ± 0.62	BCE 5220–3980	Early, middle and younger Neolithic
GI0131	Baar	Mag	1_14	M2	62	Central age model	25 ± 1.5	6.1 ± 0.6	BCE 4690–3490	Middle and Younger Neolithic
GI0247	Baar	Fue	9	M4	125	Central age model	15.71 ± 0.54	5.26 ± 0.42	BCE 3670–2830	Younger and Late Neolithic
GI0296	Baar	Gru	8_14	M2	72	Central age model	13.48 ± 0.66	4.4 ± 0.4	BCE 2790–1990	Final Neolithic
GI315	Black Forest	Leh	3	2 M3	71	Central age model	14.02 ± 0.94	4.3 ± 0.4	BCE 2690–1890	Final Neolithic

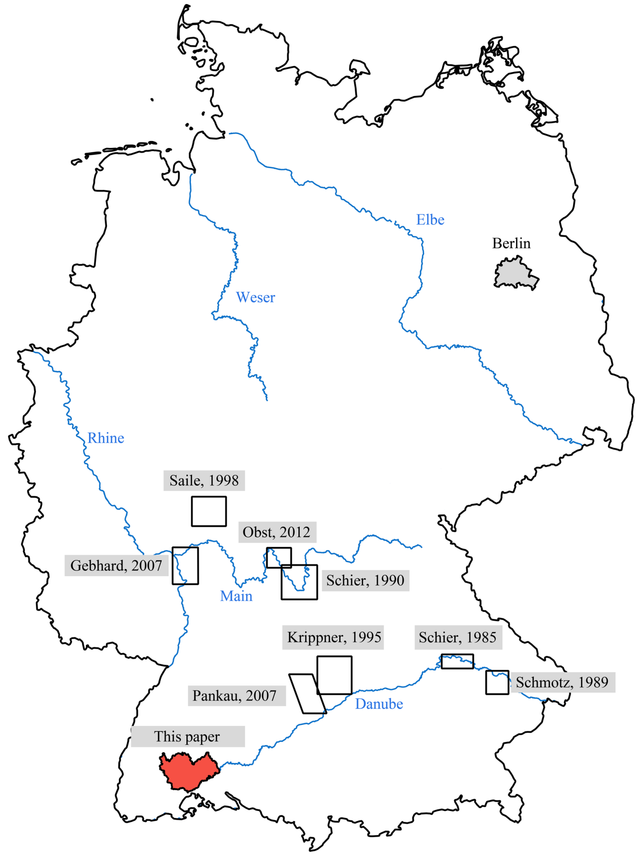

Figure 6. Location of study areas used in discussion on local site frequencies (see Table 6).

the archaeopedological studies indicate settlement dynamics on the western Baar region. At Grüningen, both an AMS ^{14}C age (Erl-20137) and a luminescence age (GI0296) from Gru8_14 point to the formation of a colluvial deposit during the Final Neolithic. Furthermore, AMS ^{14}C dating of charcoals demonstrates a human presence at Fürstenberg (Erl-20275) and Geisingen (P 13418).

4.2.3 The Swabian Jura

The archaeopedological studies suggest similar developments in the Baar region and on the Swabian Jura, even though the number of AMS ^{14}C and luminescence datings are significantly smaller on the Swabian Jura. A radiocarbon age from Königsheim (P 12910) points to land use on the Heuberg in the Early Neolithic. The Middle Neolithic is represented by two radiocarbon ages from the Swabian Jura. Whereas the AMS ^{14}C dating from Königsheim (P 12910) covers both the early and the Middle Neolithic, and the charcoal sample from Lindenberg (P 12903) dates into this period suggesting a more frequent human presence in the eastern Baar and in the small river valleys between the high plateaus of the Swabian Jura. Younger Neolithic land use on the Swabian Jura can be demonstrated by using a charcoal sample from the Lindenberg soil profile (P 12896). So far, there have been no indications of a formation of colluvial deposits during this period on the Heuberg. The transition to the Late Neolithic is characterized by a continuous formation of colluvial deposits on the Lindenberg (P 12897) and a new phase of land use on the Heuberg at Königsheim (P 12907). In the Final Neolithic, an intensification of land use on the Heuberg is indicated as the formation of colluvial deposits can be demonstrated in soil profiles at Böttingen (P 12888) and Königsheim (P 12907). In addition, charcoal fragments from a colluvial deposit point to an ongoing land use on the Lindenberg (P 12900, P 12925).

4.2.4 The Black Forest

In general, the archaeopedological studies indicate a low human impact in the Black Forest during the Neolithic. Nevertheless, it is striking that the earliest indications of an anthropogenically triggered formation of colluvial deposits in this landscape date to the Younger Neolithic (P 12871). This period is characterized by a significant increase in data for colluviation in the adjacent Baar region suggesting an intensification and expansion of land use. Apparently this was accompanied by a more frequent human presence in the Black Forest. Furthermore, Late Neolithic land use in the Black Forest is indicated by an AMS ^{14}C age from the spring source of the river Brigach (P 12865). Radiocarbon ages from both the river Brigach (P 12920) and Lehmgrubenhof (GI0315) also point to phases of human presence in the Final Neolithic. The fact that charcoal samples from the spring source area of the river Brigach date into the Late and Final Neolithic may be an indication that humans followed the larger rivers as they entered this landscape. This is also suggested by archaeological finds from the western Baar (Ahlrichs et al., 2016) and by the fragment of a Neolithic blade made of Cretaceous chert found in the colluvial deposits at the spring source of the river Breg (Henkner et al., 2018c).

5 Discussion of Neolithic settlement dynamics

5.1 Early Neolithic (5500–5000 cal BCE)

During the Early Neolithic, the study area was sparsely populated (Fig. 7). The archaeological record demonstrates human land use in the vicinity of Villingen-Schwenningen at the river Brigach and the spring source of the river Neckar as well as at the Danube in the southern Baar and in the valleys of the Swabian Jura. The pedological data support these archaeological results. Both at the Magdalenenberg (GI0132) and the Fürstenberg (GI0183, GI0184, GI0248, Erl-2027), phases of colluviation were detected dating to the Early Neolithic. In addition, the dating of charcoal sample P 12910 from Königsheim indicates a phase of land use on the Heuberg, a landscape, where no Early Neolithic sites are known so far. The location of Early Neolithic settlements in the immediate vicinity of large rivers in other areas was interpreted in a way that the early farmers followed large rivers when they colonized new territories (Schier, 1990; Bofinger, 2005). Similar locations of settlements were discovered at the river Neckar and in close proximity to the Danube in the Baar region (Ahlrichs, 2017). The artefacts from the settlement at the river Neckar indicate that Neolithic farmers penetrated the Black Forest to extract raw materials. Several grinding stones found in the settlement were made of a type of rock that occurs only in the Black Forest. Furthermore, chunks of haematite were recovered at the site (Schmid, 1992) which was mined in the Black Forest (Ahlrichs, 2015).

5.2 Middle Neolithic (5000–4400 cal BCE)

Archaeologically, the Middle Neolithic is characterized by a low site density (Fig. 7). However, the site distribution indicates a continuation of the settlement patterns introduced in the Early Neolithic. In contrast to the Early Neolithic, there is archaeological evidence for hilltop settlements in the southern and eastern Baar. Trends like these have also been observed in the Maindreieck (Schier, 1990) and the Obere Gäue (Bofinger, 2005). In addition, there are archaeological indications of a human presence in the northern Baar and an expansion into the northeastern Baar. However, the artefacts recovered from these four sites cannot be assigned to the Middle Neolithic with absolute certainty as they are also typical for later periods (Ahlrichs, 2017). The pedological data are consistent with the site distribution: radiocarbon and luminescence ages point to a formation of colluvial deposits in the northern Baar (GI0131) and on the Swabian Jura (P 12896, P 12903, P 12910).

5.3 Younger Neolithic (4400–3500 cal BCE)

The transition to the Younger Neolithic is characterized by significant reduction in the archaeological data (Fig. 7). This is in strong contrast to other landscapes in southwest Germany where Neolithic farmers expanded their territories (Bofinger, 2005). So far, only one site from the northeastern Baar can be dated directly to this period. Furthermore, there are four sites in the northern Baar and two in the southern Baar dating to the Younger Neolithic. In contrast to the archaeological data, both AMS ^{14}C ages and OSL ages from colluvial deposits indicate land use at the Magdalenenberg (Poz-36954, Erl-20132, GI0131), in the vicinity of Spaichingen (P 12878), at the Fürstenberg (GI0183, GI0184, GI0247, GI0248) and on the Swabian Jura (P 12896). So far, there are neither archaeological nor pedological indications of land use on the Heuberg. However, pollen analysis of a bog profile from Elzhof and a radiocarbon age from Lehmgrubenhof (P 12871) in the southeastern Black Forest point to changes in the vegetation caused by land use during the Younger Neolithic (Henkner et al., 2018a, c). These developments are in line with archaeological and archaeobotanical studies

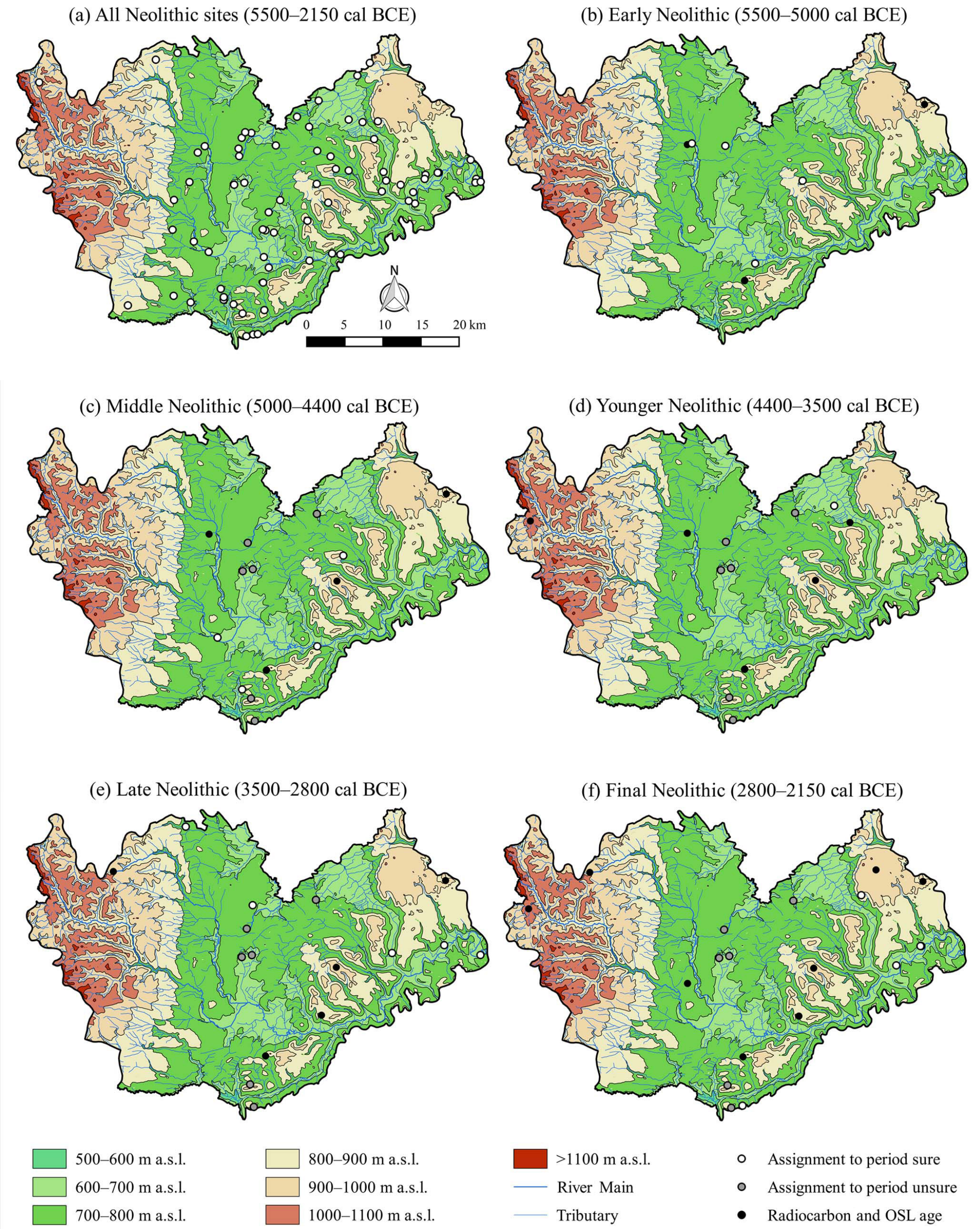

Figure 7. Distribution of all recorded Neolithic sites **(a)** and reconstruction of Neolithic settlement dynamics during the **(b)** Early Neolithic, **(c)** Middle Neolithic, **(d)** Younger Neolithic, **(e)** Late Neolithic and **(f)** Final Neolithic.

from other parts of the Black Forest. Based on archaeological field surveys (Valde-Nowak, 1999; Kienlin and Valde-Nowak, 2004; Valde-Nowak and Kienlin, 2002) and pollen records (Frenzel, 1982, 1997; Rösch, 2009), human presence can be demonstrated in the western and northern areas of the Black Forest during the Younger Neolithic. Basically, the archaeological and archaeobotanical results are interpreted as an indication of seasonal land use in the Black Forest, i.e. in the context of a transhumance (Valde-Nowak, 2002). This form of land use leaves few archaeological traces because of its seasonal character and the fact that small mobile groups of shepherds are travelling along with the livestock. In addition, these sites are difficult to find due to the recent reforestation of the Black Forest and sites may have been redeposited or covered by slope deposits (Lais, 1937; Paret, 1961; Pasda, 1998).

Henkner et al. (2017) calculated the summed probability density (SPD) of the radiocarbon and luminescence ages for the Baar region. The oldest phase of increased colluvial deposition dates to the Younger Neolithic, where the increase in formations of colluvial deposits took place in a wetter- and colder-climate period. Therefore, higher erosion rates may have been caused by higher amounts of precipitation. Furthermore, the agricultural technology went through major changes during the Younger Neolithic. During the early and Middle Neolithic fields were ploughed manually, whereas farming became more efficient in the Younger Neolithic since new types of ploughs (pulled by cattle) were introduced (Lüning, 2000). This change opens up the possibility of cultivating larger fields, which may have increased local soil erosion processes.

5.4 Late Neolithic (3500–2800 cal BCE)

The transition to the Late Neolithic is marked by significant changes in the local settlement pattern (Fig. 7). In contrast to previous periods, several sites were established in the Danube Valley. In the northwestern Baar, a site is situated in a small river valley leading into the Black Forest. This can be taken as an indicator for a temporary human presence in this landscape. Additionally, archaeobotanical analysis of pollen profiles from Elzhof and Moosschachen documented a small human impact during the Late Neolithic in the Black Forest (Henkner et al., 2018c). Furthermore, pedological analysis of colluvial deposits point to human activities on the Heuberg at Königsheim (P 12907) and on the Lindenberg (P 12897, P 12900). Consequently, the Late Neolithic is the first period in which Neolithic societies expanded simultaneously their territories into the eastern Black Forest and western Swabian Jura. The pedological investigations of colluvial deposits at Fürstenberg (Erl-20276, Erl-20277, GI0247) and Geisingen (P 13418, P 14445) point to a human presence in the southern and southeastern Baar during the Late Neolithic for which archaeological evidence still has to be provided.

5.5 Final Neolithic (2800–2150 cal BCE)

The general Late Neolithic settlement pattern prevailed during the Final Neolithic (Fig. 7). However, for the first time, there is archaeological evidence for a Neolithic settlement on the Heuberg. The analysis of a colluvial deposit at Böttingen points to human presence near this settlement (P 12888). Furthermore, AMS ^{14}C and OSL dates indicate a phase of colluvial deposition at Grüningen in the western Baar (Erl-20137, GI0296).

6 Conclusion

We investigated Neolithic settlement dynamics by using an integrated archaeological–archaeopedological approach with a focus on archaeological source criticism and colluvial deposits. Our results lead to the following conclusions.

- Archaeological source criticism indicates that Neolithic settlement dynamics in our study area cannot be described based on the archaeological data alone. The distribution pattern of the sites especially in the low mountain ranges seems to be influenced by various factors: (i) a restricted accessibility of sites due to dense vegetation in forests in the Black Forest and on the Swabian Jura, (ii) a superimposition of sites by colluvial deposits and (iii) weathering effects on the preservation of pottery. These factors contribute to the difficulty of discovering new Neolithic sites by field surveys. Consequently, the Neolithic site frequencies are very low compared to other regions in southwestern Germany.

- A more reliable picture of Neolithic settlement dynamics is achieved by complementing archaeological data and chronological data from colluvial deposits. Thus, we were able to describe settlement dynamics not only between the Baar region and the adjacent low mountain ranges but also within the Baar region for the different chronological levels of the Neolithic.

- Archaeopedological results indicate a continuous land use at the Fürstenberg throughout the Neolithic. This site might have been a particular favourable location because of its proximity to the Danube, which probably served as an important route for communication and trade. This is also suggested by rare imported objects found at the Fürstenberg and in the Danube Valley.

- Archaeological finds point to expeditions into the Black Forest for the extraction of raw material for stone tools and haematite in the Early Neolithic. The formation of colluvial deposits in the eastern Black Forest and western Swabian Jura was triggered most probably by transhumance and small-scale farming in the Late and Final Neolithic.

Data availability. The data used in this paper are stored at Dryad (https://doi.org/10.5061/dryad.rh67h, Henkner, 2018b). Additional information and supplementary data about this project are published (Ahlrichs et al., 2016, 2018a, b; Ahlrichs, 2017; Henkner et al., 2017, 2018a, c).

Author contributions. JJM, JH, PK, TS and TK designed the study, and JJM carried it out. JJM prepared the manuscript with contributions from all co-authors. MF was responsible for OSL dating. KS contributed to the interpretation and discussion of the results of the quantitative analyses.

Competing interests. The authors declare that they have no conflict of interest.

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Research article

Fortification, mining, and charcoal production: landscape history at the abandoned medieval settlement of Hohenwalde at the Faule Pfütze (Saxony, Eastern Ore Mountains)

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Abstract: Geoarchaeological reconstructions of land-use changes may help to reveal driving cultural factors and incentives behind these processes and relate them to supra-regional economic and political developments. This is particularly true in the context of complete abandonment of a settlement. Here we present a case study from the site of Faule Pfütze, a small catchment in the Eastern Ore Mountains (Saxony). The historical record of this site is confined to the report of a settlement called Hohenwalde in 1404 CE and two later references to the then-abandoned settlement in 1492 and 1524 CE in this area. Combined geoarchaeological studies allowed for the reconstruction of several phases of land use. While a first phase of alluvial sedimentation occurred during the late 12th century, archaeological evidence for a permanent settlement is absent during this period. The onset of settlement activity is identified during the late 14th century and included a hitherto unknown massive stone building. Mining features are present nearby and are dated to the early 15th century. The local palynological record shows evidence for reforestation during the mid 15th century and thereby corroborates the time of abandonment indicated by written sources. These processes are discussed in the context of a local political conflict (Dohna Feud) leading to the redistribution of properties and the development of a mining economy during this time. Later land use from the mid 16th century onwards appears restricted to charcoal production, probably in the context of smelting works operating in nearby Schmiedeberg as indicated by rising lead concentrations in the alluvial record.

Kurzfassung: Geoarchäologische Rekonstruktionen der Landschaftsgeschichte können dazu dienen, die hinter diesen Prozessen liegenden kulturellen Triebkräfte und Motivationen offenzulegen und diese mit überregionalen ökonomischen und politischen Entwicklungen in Beziehung zu setzen. In besonders hohem

Maße trifft dieses im Umfeld von vollständigen Wüstungsprozessen zu. Im Rahmen einer Fallstudie wird hier die Fundstelle an der "Faulen Pfütze", einer kleinen Siedlungskammer im Osterzgebirge (Sachsen), vorgestellt. Die historische Überlieferung zu dieser Fundstelle beschränkt sich auf die Nennung einer Siedlung "Hohenwalde" im Jahr 1404 sowie zwei spätere Nennungen aus dem Jahr 1492 und 1524, die sich bereits auf eine Wüstung in diesem Gebiet beziehen. Nur durch geoarchäologische Ansätze war es daher möglich, unterschiedliche Phasen der Landnutzungsgeschichte zu rekonstruieren. Während eine erste Phase der alluvialen Sedimentation bereits im späten 12. Jahrhundert festzustellen ist, fehlen archäologische Belege für eine dauerhafte Siedlung zu diesem Zeitpunkt noch völlig. Der Beginn der Siedlungsaktivitäten setzt im späten 14. Jahrhundert ein und umfasst dabei auch ein bislang unbekanntes massives Steingebäude. In unmittelbarer Nähe treten Bergbauspuren auf, die in das frühe 15. Jahrhundert datieren. Die palynologischen Analysen zeigen eine lokale Wiederbewaldungsdynamik ab der Mitte des 15. Jahrhunderts und bestätigen dabei den durch historische Quellen genannten Zeitpunkt der Siedlungsaufgabe. Diese Entwicklung wird vor dem Hintergrund eine regionalen Auseinandersetzung (Dohnaischen Fehde) diskutiert, die vor Ort nicht nur eine territoriale Neuverteilung sondern auch Bergbauaktivitäten zur Folge hatte. Spätere Landnutzung ab der Mitte des 16. Jahrhunderts scheint dann auf die Produktion von Holzkohle beschränkt gewesen zu sein, wahrscheinlich zur Versorgung der Hüttenwerke im nahen Schmiedeberg, was sich auch in steigenden Bleieinträgen in den alluvialen Sedimenten abzeichnet.

1 Introduction

A number of regional case studies have highlighted the influence of mining activities and related timber and charcoal production on central European mountain ranges (e.g. Stolz and Grunert, 2010; Hrubý et al., 2014; Knapp et al., 2015). In the Ore Mountains region silver and tin mining has been present at least since the mid 12th century based on historical sources (Wagenbreth, 1990), but archaeological and palaeoenvironmental investigations on this time period have been scarce compared to other regions. Due to the establishment of a border zone between East Germany and the Czechoslovakia from 1945 to 1990 and low construction activities, this area has not been in the focus of the heritage authorities on both sides of the border for decades. Moreover, the intensive mining activities in later centuries were expected to have destroyed most of the medieval structures. Palaeoenvironmental studies were restricted to pollen profiles from mires in the upper reaches of the Ore Mountains (Stebich, 1995; Schlöffel, 2010). Research activity in this area only resumed after the discovery of well-preserved mining features from the late 12th and 13th century in Dippoldiswalde in 2008 and led to the establishment of two German–Czech ArchaeoMontan research projects (Ziel-3 ArchaeoMontan from 2012 to 2015 and ArchaeoMontan 2018 from 2016 to 2018). In the course of these projects, local studies focussed on the medieval human impact around the town of Freiberg that have flourished as a silver mining centre since the mid 12th century (Tolksdorf et al., 2018) and the effects of mining activities together with timber and charcoal production since the late 12th century in the small mining district of Niederpöbel near Schmiedeberg in the Eastern Ore Mountains (Schröder, 2015; Tolksdorf et al., 2015). The results have indicated a strong impact in the form of deforestation, a sharp decline of tree species like *Abies alba* and changes in forest composition during ongoing land use. This case study addresses the land-use history of a comparatively short-lived village in the Ore Mountains in the context of local mining activities and the regional political history.

2 Site topography and sampling

The site of Faule Pfütze is located in the Eastern Ore Mountains (*Osterzgebirge* in German) about 30 km south of Dresden (Fig. 1a) in a mountain ridge east of Schmiedeberg (Fig. 1b) and was investigated by the ArchaeoMontan 2018 team in 2016 and 2017. Local geology is dominated by quartz porphyries and porphyroid granites (GK 25, 1915; Reinisch, 1915). In the study area the small valley of the Brießnitzbach river opens to the east, and the modern site name "Faule Pfütze" (meaning "brackish pool" in German) relates to the wetlands around the spring area of this river. Microtopographical assessment of lidar data reveals several sunken roads that converge in the area of a modern dam used for the road, creating a small pond. Some mining features (shafts, mining heaps) can be recognized by their specific topography to the southeast. Additional charcoal kilns in the form of round platforms are visible on the surrounding slopes (Fig. 2a).

Immediately downstream of the modern dam, the upper 110 cm of alluvial sediments was accessible in an outcrop cut by the river and sampled as profile 1 for macro-botanical, palynological, geochemical, and ^{14}C analyses. A dense layer of rubble just a few metres upstream of profile 1 was noted as an archaeological feature and labelled profile 3. To substantiate the age of the mining features, profile 2 was situated beside

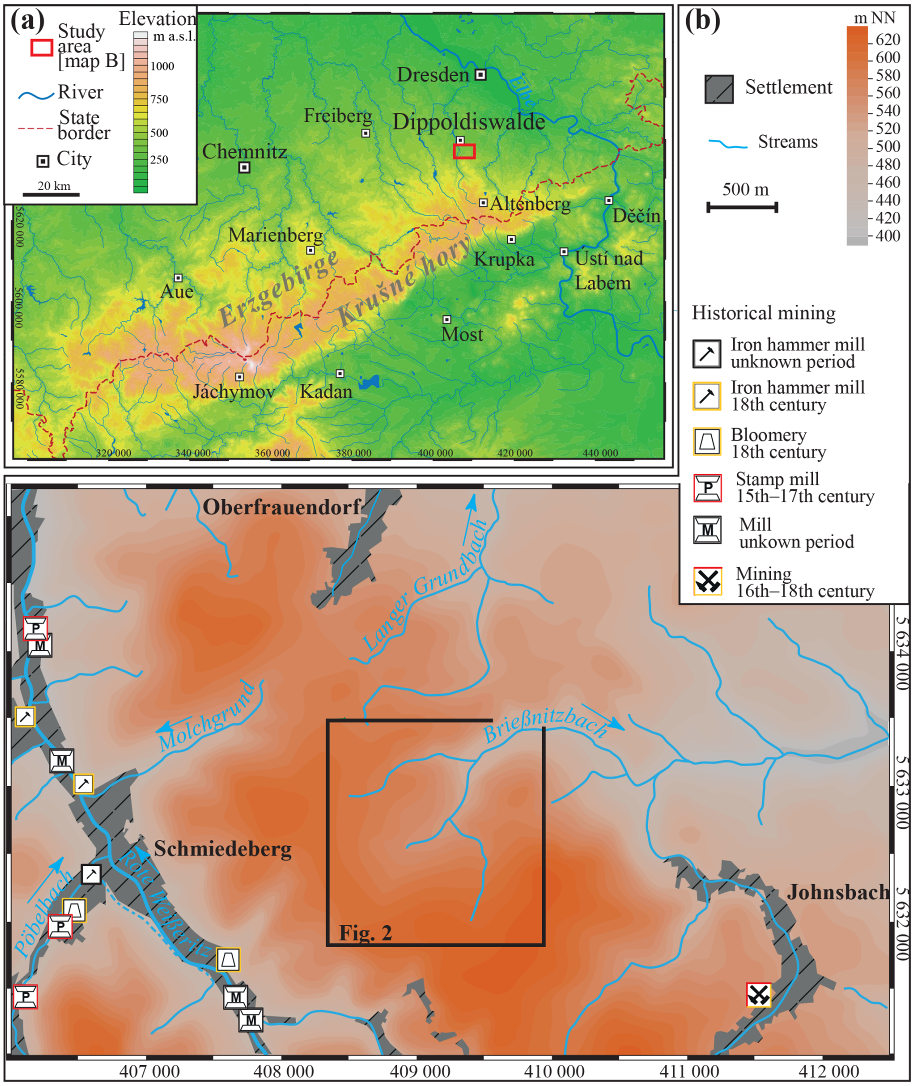

Figure 1. **(a)** Location of the site of Faule Pfütze in the Ore Mountains (data: SRTM), **(b)** regional topography (data: GeoSN). Historical mining features are mapped according to historical maps (Ur–Oder and Oeder–Zimmermann from early 17th century) and written sources (Müller, 1964) using the symbols and time periods from Göhler and Wehmeyer (2013).

a mining heap in order to sample the palaeo-surface covered by mining waste for botanical (BOT-36) and ^{14}C analyses (MAMS-30882).

The valley bottom above profile 1 yielded numerous ceramic fragments on the surface. Here, profile 4 was recorded to document the relation of settlement layers to alluvial and colluvial sediments, while profile 5 was situated at the transition from the southern hillslope to the alluvial plain. A prominent feature visible in the digital elevation model (DEM) derived from lidar scan is a stone heap with a square layout rising more than 1 m above the valley floor. Profile 6 was used to record a profile in this feature and profile 7 was used for archaeological investigation of the valley floor nearby. Sedimentation history on the valley floor was recorded using a transect consisting of six cores and profiles 1 and 3 (Fig. 2b) from the southeast to the northwest.

3 Methods and material

Botanical macro-remains were retrieved from sediment samples by wet sieving with mesh widths of 2, 1, 0.5, and 0.25 mm and determined according to standard literature (Cappers et al., 2012) and a reference collection of wild and domestic plants. Their attribution to ecological groups is based on the classification by Oberdorfer (2001). Sample preparation for pollen analysis followed standard acetolysis procedure, and a minimum number of 500 palynomorphs were identified according to literature (Beug, 2004) in every sample. A portable X-ray fluorescence (XRF) unit (Olympus

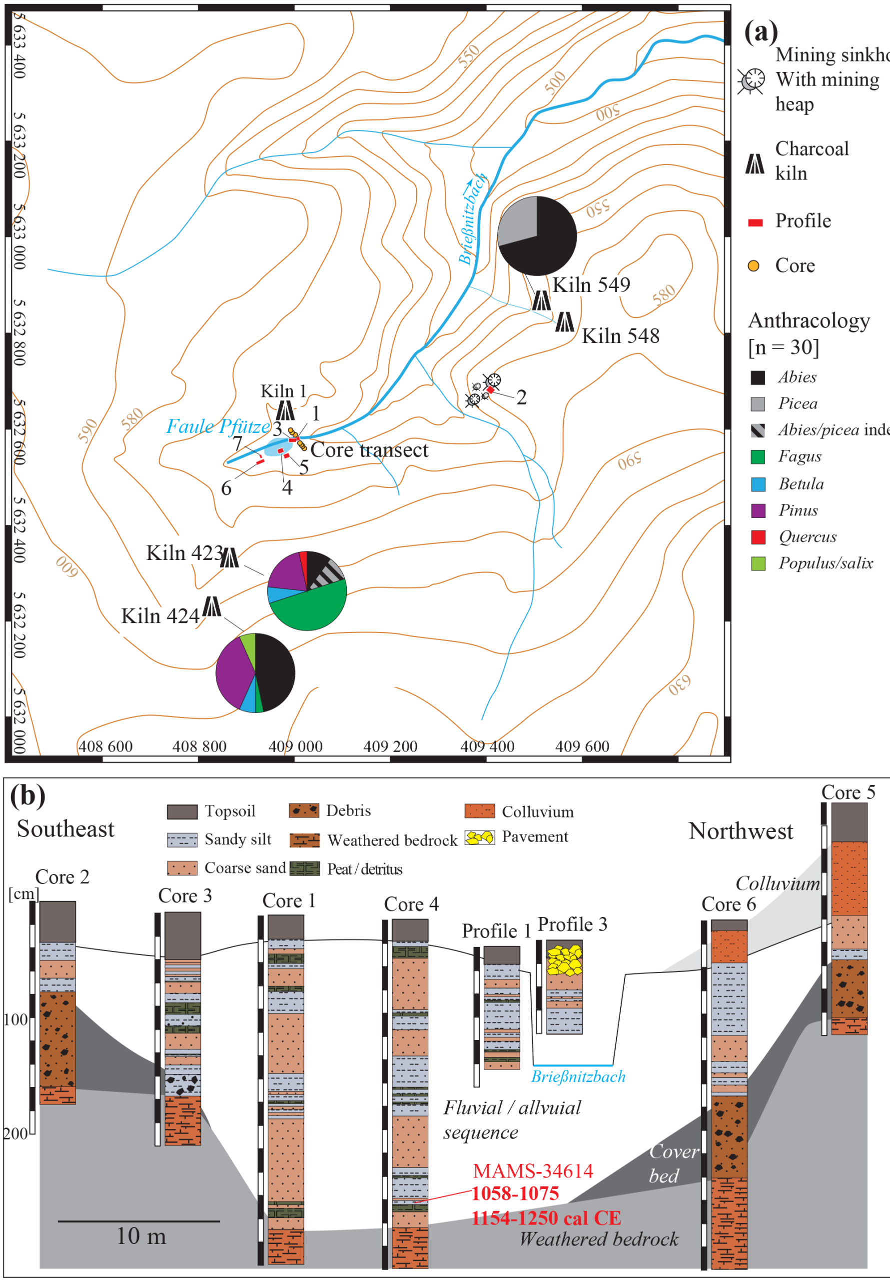

Figure 2. **(a)** Site topography, sampled records, and results of anthracological analysis of charcoal kilns from this area; **(b)** stratigraphic logs of the core transect through the valley floor.

Innov-X DELTA 50) was used to measure geochemical properties on dried samples from the grain-size fraction < 0.8 mm (CGS Prague Laboratories). Changing concentrations of the elements Pb, As, and Zn were used as potential environmental proxies for metallurgical activities (Hürkamp et al., 2009; Schmidt-Wygaasch et al., 2010). The ^{14}C analyses were performed by the Curt-Engelhorn-Zentrum Archäometrie (CEZ) in Mannheim, and calibrated using IntCal13 (Table 1) and the Bayesian model implemented in OxCal. Samples of 30 charred particles were extracted from three charcoal kilns for an anthracological assessment. Determination of the taxa is based on wood-anatomical features on fresh cuts with different orientations (Schweingruber, 1990). Due to their anatomical similarity *Populus* and *Salix* were grouped together. The dating of ceramics was based on typological and technological parallels with well-dated archaeological assemblages in the region (Mechelk, 1981). A series of overlapping photos was used to process 3-D models for larger archaeological features by structure from motion (SfM). Consequently, the

Table 1. Results of ^{14}C analyses.

Lab no.	Profile	Material and context	^{14}C	^{14}C (calibrated; IntCal13, 1σ)	^{14}C (calibrated; IntCal13, 2σ)	δ^{13}C (‰)
			(BP)	(cal CE)	(cal CE)	
MAMS-30884	profile 1	charcoal from alluvial layer 18–25 cm below surface	282 ± 16	1528–1544 1634–1650	1522–1573 1630–1657	−23.6
MAMS-30883	profile 1 from alluvial layer	charcoal 49–55 cm below surface	333 ± 17	1499–1504 1512–1527 1555–1601 1617–1633	1487–1638	−23.9
MAMS-32962	profile 1	charcoal from alluvial layer 75 cm below surface	401 ± 19	1447–1479	1441–1498 1601–1616	−17.6
MAMS-30882	profile 2	charcoal below mining heap	510 ± 17	1414–1430	1408–1437	−23.1
MAMS-33862	profile 4	charcoal concentration below alluvial layers, 55 cm below surface	953 ± 22 1086–1124	1029–1049 1065–1155 1137–1150	1023–1059 1065–1155	−25.7
MAMS-33861	profile 6	charcoal, under embankment 80 cm below surface	593 ± 24	1315–1356 1389–1400	1300–1369 1381–1410	−29.2
MAMS-34614	core 4	charcoal from base of alluvial sediments	857 ± 23	1167–1214	1058–1075 1154–1250	−29.0
MAMS-32530	charcoal kiln 423	charcoal kiln	311 ± 21	1522–1575 1586–1590 1625–1642	1495–1602 1616–1646	−23.9

structures were mapped in a local coordinate system with the surrounding surface as the vertical reference level.

4 Results

The auger transect through the valley floor around profile 1 shows a complex sequence of coarse fluvial sands and alluvial silt that partly cover the periglacial cover beds dominated by gravels (Fig. 2b). Fine layers of organic detritus were preserved within some of the alluvial silt units. Colluvial layers appear at the northern slope covering the alluvial layers. A ^{14}C sample from the lowermost alluvial layer in core 4 yielded an age of 1058–1075 or 1154–1250 cal CE (MAMS-34614).

Profile 1 was recorded at a location where the river at the outlet of the modern dam incised into the valley floor. The sequence exposed along the bank consists of alluvial layers with organic detritus and coarse fluvial sands (Fig. 3). Based on three ^{14}C analyses (MAMS-30883, MAMS-30884, MAMS-32962), these layers have been deposited from the early 15th century to the early 17th century. The content of botanical macro-remains differs between the alluvial layers but is consistently dominated by wetland taxa. The ratio of arboreal to non-arboreal pollen within the three lowermost pollen samples shows recovering forest vegetation up to a depth of 61 cm. The sample at 55 cm is characterized by a high percentage of micro-charcoal and declining arboreal pollen. Geochemical analyses show a relatively stable concentration of zinc and arsenic but a distinct rise in lead concentrations at a depth of about 50 cm. Based on the chronological model, both the drop of arboreal pollen and the rise of lead content are ascribed to the 15th to 16th century.

The detailed analysis of the pollen spectra (Fig. 4) reveals a very high percentage of *Corylus avellana* pollen in the lowermost sample at 90 cm. The subsequent samples at 75 cm show a sharp decline of *Corylus* but increasing percentages of *Abies*, *Pinus*, and *Picea* pollen. At a depth of 61 cm the share of *Abies* pollen declined again while *Pinus* and *Picea* are still expanding. Although pollen from *Secale cereale* and *Centaurea cyanus* as well as ruderal taxa like *Plantago lanceolata* or *Rumex acetosella* are present in these lower three samples, their low number indicates that permanent settlement and arable land could have existed only at some distance. Additional information about the local vegetation is provided by the macro-botanical spectra at 75, 67, and 61 cm depth. These present a dominance of wetland

Table 2. Macro-botanical and anthracological results.

Sample (BOT: macro-remains; HK: anthracology) cf. Figs. 2 and 3 for sample location				BOT-53	BOT-54	BOT-62	BOT-63	BOT-64	BOT-65	BOT-36	BOT-79	BOT-80	BOT-85	HK-14	HK-15	HK-16
Sample size (litres or pieces (pcs.))				0.11	0.11	0.11	0.11	0.11	0.11	0.21	0.11	0.11	0.11	30 pcs.	30 pcs.	30 pcs.
Depth (cm)				75	47	51	56	61	67	120	14–29	29–49	200	10	10	10
Profile				1	1	1	1	1	1	2	4	4	4	kiln 423	kiln 424	kiln 529
	Taxonomy	Anatomy	Preser-vation													
Forest community	*Abies alba*	ND	u	5		9		4	9				2			
		ND	ch			21				500		36	180			
		W	ch											3	14	17
	Picea abies	ND	u	9				11	11		23	7				
		ND	ch			4										
		W	ch													7
	Abies and *Picea* indet.	W	ch											3		
	Pinus	ND	ch							5						
		W	ch											6	11	
	Populus sp.	FS	u					1	1							
		W	ch												1	
	Populus and *Salix* indet.	W	ch												1	
	Carpinus betulus	FS	ch							1						
	Fagus sylvatica	W	ch											15	1	
	Quercus robur	W	ch											1		
	Oxalis acetosella	FS	u		1	1										
Forest edges and clearances	*Arctium* sp.	FS	u				1									
	Betula pendula and	FS	u	11		1			6							
	pubescens	W	c											2	2	
	Carex ovalis	FS	u				1	1	1							
	Hypericum hirsutum	FS	u						1							
	Sambucus nigra	FS	ch										2			
	Rubus fructicosus agg.	FS	u				1									
Meadows	*Cerastium fontanum*	R	u	4	1	5		1	3							
	Luzula campestris	FS	u		2		1									
	and *L. multiflora*															
	Origanum vulgare	FS	u		1											
	Prunella vulgaris	FS	u						1							
	Rumex acetosella agg.	FS	u			1		1								
Wetlands and river banks	*Carex* sp.	FS	u	13	1000	300	359	195	480							
	Glyceria fluitans	FS	u	114		32	50	4	115							
	Montia fontana s.l.	FS	u	41		8	4									
	Potamogeton sp.	FS	u		2											
	Ranunculus flammula	FS	u	1	4	8	17	8	8							
	Scirpus sylvaticus	FS	u	1		10	33	10	10							
	Sparganium emersum	FS	u		1											
	Sphagnum	FS	u	+												
Varia	*Chenopodium album* type	FS	u				1									
	Carduus and *Cirsium*	FS	u					1								
	Juncus sp.	FS	u	5	7	9	7	1	2		36	31	60			
	Lamiaceae	FS	u		1											
	Myosotis sp.	FS	u	1												
	Pinaceae	FS	u						1							
	Poa sp.	FS	u	5	1											
	Polygonum aviculare agg.	FS	u				2									
	Sagina procumbens	FS	u				1									
	Viola sp.	FS	u		18	1	5	1								
	Rumex crispus	FS	ch						1							
	or *R. obtusifolius*															
	Indeterminate	FS	u		1											
	Indeterminate	W	u	+	+	+		+								
	Indeterminate	W	ch	+	+	+	+	+	+							
	Indeterminate	R	u	4					4							6

taxa like *Glyceria fluitans* or *Montia fontana* with increasing numbers of *Carex* species. Remains of taxa which tend to occur on more open areas such as meadows or clearances like *Cerastium fontanum*, *Betula*, or *Carex ovalis* are seldom found and even show a decline that is in good accordance with the expansion of forest vegetation visible in the pollen. However, direct evidence of forest species like fir or pine is rare in these samples.

The trend towards a recovery of the forest vegetation seems to be interrupted at a depth of 55 cm with declining percentages of *Pinus*, *Picea*, and *Abies* pollen accompanied by rising values of *Corylus* and species related to open ar-

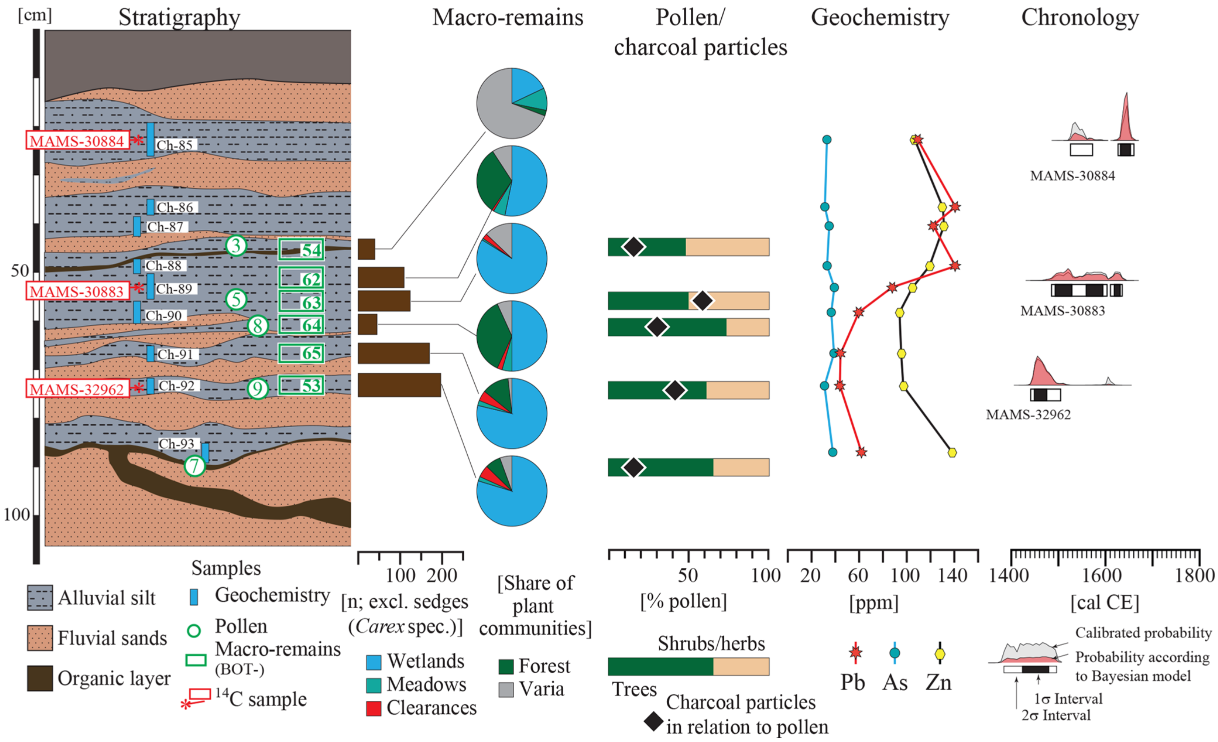

Figure 3. Stratigraphy, chronology, and key results of palynological, macro-botanical, and geochemical analyses in profile 1.

eas, especially Poaceae and Cyperaceae together with *Rumex acetosella* and *Artemisia*. The macro-botanical samples from this layer show a complete absence of taxa related to forest vegetation. While evidence for forest species is visible again in the macro-botanical spectrum at a 51 cm depth, the macro remains at a 47 cm depth and a pollen spectrum at a 45 cm depth are consistent with a reduction of forest taxa. Particularly, the very high number of *Rumex acetosella* pollen in the uppermost sample might indicate the permanent establishment of open areas, perhaps meadows.

Mining activity in this area is proven by profile 2 (Fig. 5a), which revealed a layer of charred material below a mining heap. *Abies alba* needles dominated the charred material by far (BOT-36) and prove that it results from the burning of local vegetation rather than technological processes like fire-setting or smelting. The material yielded an age of 1408–1437 cal CE (MAMS-30882) providing a minimum age for the mining activities.

The square stone heap was investigated at profile 6 (Fig. 5b) and revealed a stone wall construction covered by an embankment. Residues of the former topsoil below the embankment contained ceramic fragments, an iron nail, and charred material, yielding a ^{14}C age of 1300–1369 or 1381–1410 cal CE. It is in very good accordance with the typochronological dating of the ceramic material discovered below the layers of relocated rubble in profile 7 (Fig. 5d). This was assigned to the end of the 14th century and later based on the presence of high- and undercut-shaped collar rims (*hohe und unterschnittene Kragenränder*) and reddish high-fired earthenware (*rotscherbige hochgebrannte Irdenware*; Mechelk, 1981).

While profile 5 at the transition from the slope to the alluvial plain only yielded relocated coarse material, nearby profile 4 showed intercalating layers of alluvial sedimentation and colluvial material (Fig. 5c). At a depth of 50 cm a dense layer of charred material was covered by alluvial sediments. This material (BOT-85) was dominated by charred *Abies alba* needles but also contained remains of local *Juncus* species. Remains of *Sambucus nigra* could indicate the existence of clearances. A ^{14}C analysis provided an age of 1023–1155 cal CE for this layer. It was covered by colluvial sediments that contained charred remains of *Abies* and *Juncus* but also *Picea* needles (BOT-80). The subsequent alluvial layer from a 30 to 12 cm depth contained charred and uncharred botanical remains (*Picea* together with *Juncus* and *Carex* species) together with ceramic fragments dating to the 14th century by means of typochronology. Remains of fir were absent in this younger layer.

Some small plateaus visible in the DEM were identified as charcoal kilns (Fig. 2a). While kiln 549 only contained remains of *Abies* and *Picea*, the fuel spectra of the kilns 423 and 424 were very broad and contained *Fagus*, *Abies*, *Picea*, *Betula*, *Populus/Salix* (indiff), and *Quercus* of differing proportions. A ^{14}C analysis of kiln 423 provided an age of 1495–1646 cal CE.

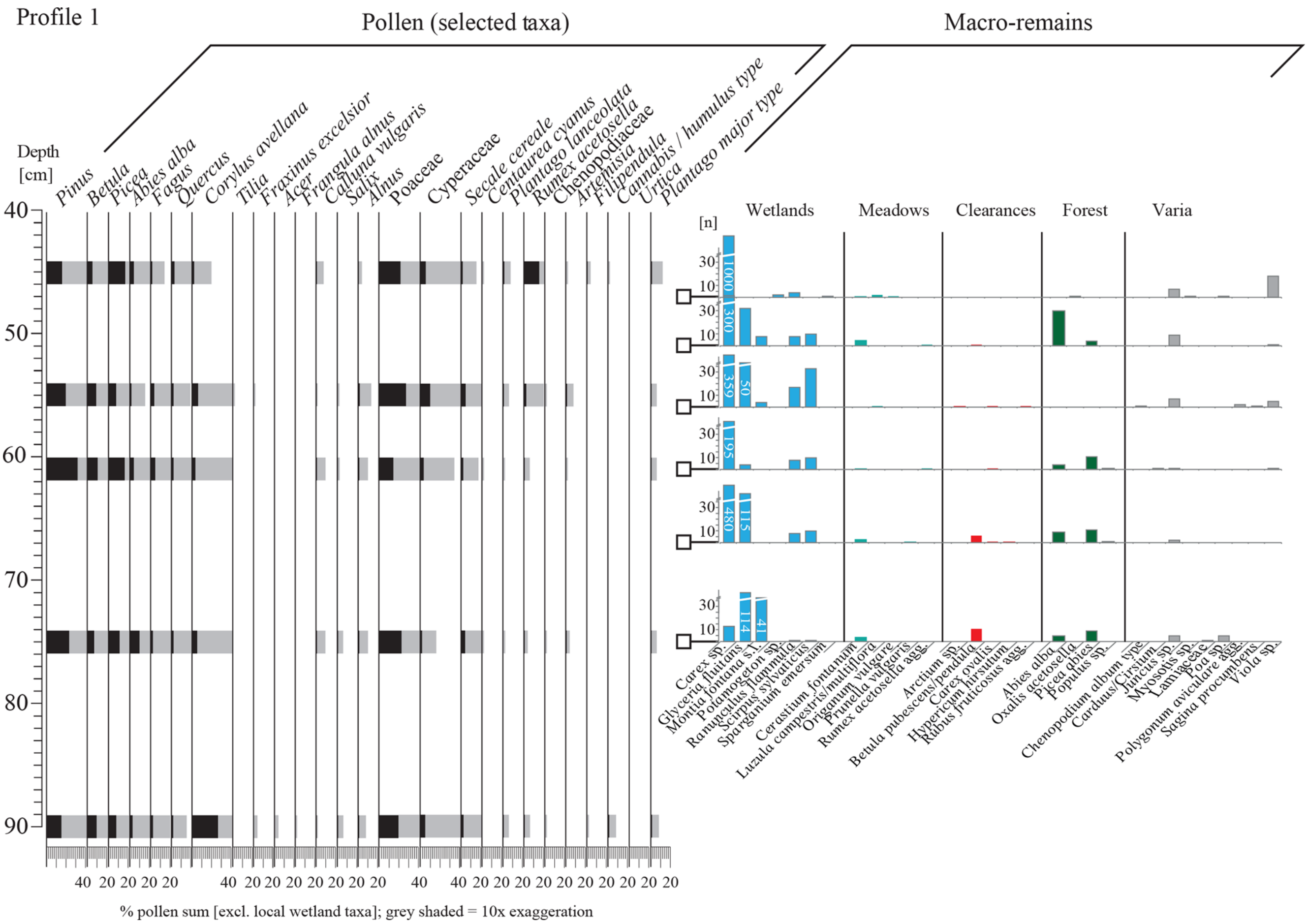

Figure 4. Palynological and macro-botanical spectra from profile 1 (cf. Fig. 3).

5 Discussion

The onset of alluvial sedimentation dates back to the 12th century based on ^{14}C ages from charcoal taken from profile 4 and core 4. Although catastrophic events like wildfires could theoretically trigger local soil erosion (Shakesby and Doerr, 2006), human impact is a more likely cause. From the regional perspective, the 12th century is known as a time period with intensive rural colonization and mining in the Ore Mountains (Billig and Geupel, 1992; Kenzler, 2013). The earliest timber from the nearby medieval mines of Dippoldiswalde (about 7 km NNW) could indicate the start of mining in the region at the turn of the 12th to the 13th century (Hoffmann, 2011; Westphal et al., 2014). However, at the site of Faule Pfütze, the artefact assemblage and archaeological features suggest permanent human activity to have occurred from the 14th century onwards. It may be possible that this settlement phase was preceded by phases of ephemeral land use with low archaeological visibility, e.g. logging or pasture. Botanical spectra from this time preceding the settlement (BOT-80, BOT-85) contain high shares of *Abies alba* (fir) needles compared to other taxa like *Picea abies* (spruce) or *Pinus sylvestris* (pine) and may indicate the dominance of fir in the forest composition. However, such evidence neither support nor preclude earlier human activities in the area.

Human settlement on this site during the 14th century is undisputed and included the construction of the massive building recorded in profiles 6 and 7. Based on the construction technique, the ground plan, and the archaeological material, this feature represents the remains of what is possibly some sort of fortification (cf. Schwabenicky, 1996), but definitely a solid stone-built structure. The onset of mining may have occurred later as indicated by the ^{14}C age from profile 2 (Fig. 6, phase 1). Identifying the political and economic context of the strong building and the mining activities is problematic as major territorial changes took place in the region after the Dohna Feud (1385–1402 CE) (Ermisch, 1902; Hoffmann, 2011). Eventually, the first historical record concerning the village of Hohenwalde in 1404 CE appears in the aftermath of these events when land ownership had changed (Müller, 1964). It is possible that mining activities have been fostered in this region by the new owner. Another aspect worth discussing is the function of the massive building. It may have either protected the settlement and

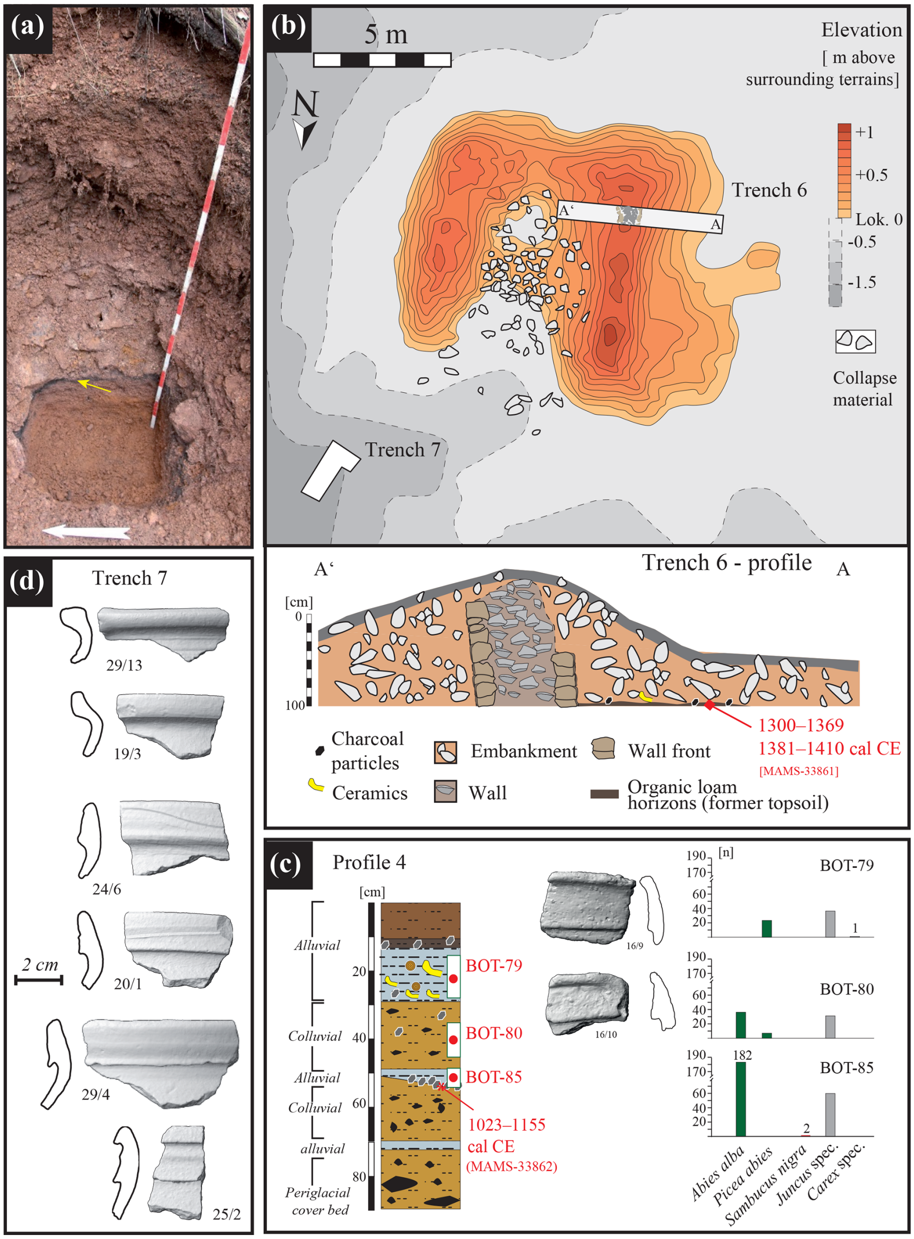

Figure 5. **(a)** Layer of burnt material (yellow arrow) below mining heap; **(b)** topography of the fortified building with profile recorded in profile 6; **(c)** profile 4 with macro-botanical analyses and chronological results; **(d)** selected artefacts from the site dating to the 14th century.

the road or been related to the protection of older mining facilities as discussed for other regions of the Ore Mountains (Schwabenicky, 1996; Kenzler, 2009). However, no historical record from this area ever refers to a fortification or mining activities, highlighting the incompleteness of this type of source. Botanical spectra from the settlement period derive from the burnt material below the mining heap (BOT-36) with abundant charred *Abies alba* needles and the upper part of profile 4 (BOT-79), where the dominance of *Picea abies* probably mirrors the local vegetation on the wet valley floor. No cultivated plants or weeds have been detected in any sample.

The abandonment of the settlement can be narrowed down by combining the historical sources mentioning an abandoned village in 1492 CE and the ^{14}C time depth model in profile 1. Here the beginning of the ecological succession is dated to the mid 15th century (Fig. 6, phase 2), marked by a high share of pioneer taxa like *Corylus avellana* (hazel) and the absence of settlement indicators. During later decades, *Abies*, followed by *Picea* and *Pinus*, established in the area. Layers dated to the mid 16th century in profile 1 reveal a de-

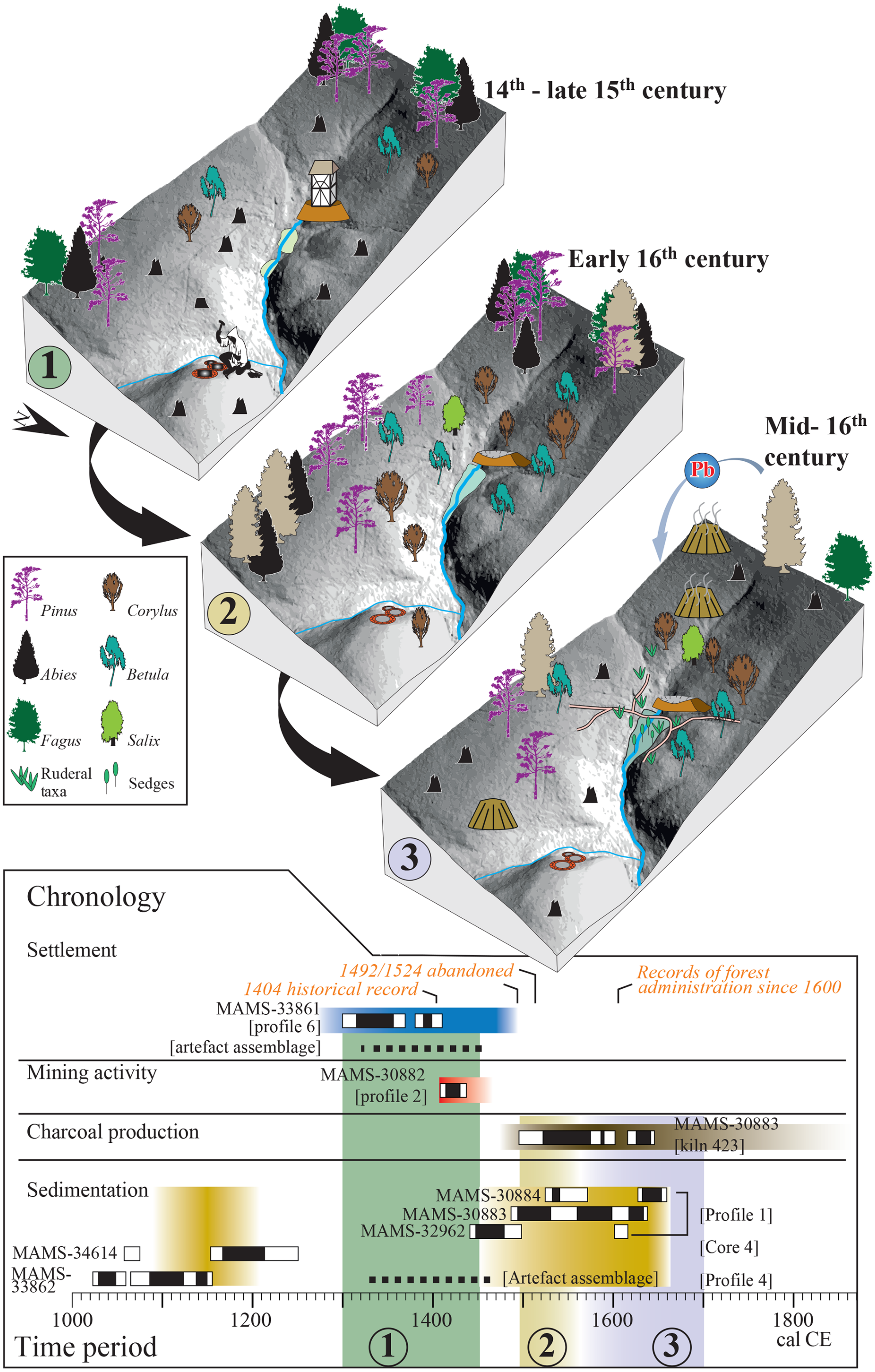

Figure 6. Reconstruction of land-use history at the site. Phase 1: settlement and mining activities during the 14th and early 15th centuries; phase 2: recovering forest vegetation after the settlement was abandoned in the mid 15th century; phase 3: metallurgical plants in Schmiedeberg since the mid 16th century prompt charcoal production and cause increased lead pollution.

clining share of arboreal pollen and rising contents of charcoal particles (Fig. 6, phase 3). This suggests resuming land use in this area, probably for the purpose of charcoal production. It is supported by a ^{14}C date of 1495–1602 or 1616–1646 cal CE (MAMS-32530) from charcoal kiln 423 and historical sources from the late 16th century (Reinhold, 1942). Rising lead concentrations in the upper part of profile 1 probably result from intensified metallurgical activities in nearby Schmiedeberg (2 km E) where smelting works were established during this period (Müller, 1964). While the pollen spectra capture a rising percentage of spruce in this area, the spectra from the charcoal kilns are more diverse, with pioneer taxa like *Betula* on the one hand and forest taxa like *Fagus sylvatica* and *Abies alba* on the other hand, and may simply reflect the natural local vegetation variety. The use of this area for logging and charcoal production continued until modern times; today the area is mainly covered by *Picea* plantations.

6 Conclusions

Our results indicate local settlement activities at least since 14th century CE and the existence of a strong building in this settlement may point towards the need to secure the area and its resources during this time period. It is likely that this area was affected by political reorganization following a feud in 1402 CE, and mining activities dating to the early 15th century may relate to a changed political and organizational background of the settlement that must have failed since the mid 15th century as indicated by reforestation and historical sources. Land use shifted to charcoal production to supply the striving metallurgical activities in the nearby Schmiedeberg area since the 16th century CE.

Data availability. All raw data and artefacts are stored at the Landesamt für Archäologie Sachsen (dataset code: OFD-01) and can obtained upon reasonable request.

Author contributions. Fieldwork was performed by JFT, MS, FS, and MB under the project supervision of CH. Pollen analysis was done by LP, anthracological analyses by PK, and analysis of botanical remains by CH. JFT prepared the manuscript and figures.

Competing interests. The authors declare that they have no conflict of interest.

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Research article

Sediment-filled karst depressions and *riyad* – key archaeological environments of south Qatar

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Abstract: Systematic archaeological exploration of southern Qatar started in the 1950s. However, detailed local and regional data on climatic fluctuations and landscape changes during the Holocene, pivotal for understanding and reconstructing human–environment interactions, are still lacking. This contribution provides an overview on the variability of geomorphic environments of southern Qatar with a focus on depression landforms, which reveal a rich archaeological heritage ranging from Palaeolithic(?) and Early Neolithic times to the Modern era. Based on a detailed geomorphic mapping campaign, sediment cores and optically stimulated luminescence data, the dynamics of *riyad* (singular *rawdha*; shallow, small-scale, sediment-filled karst depressions clustering in the central southern peninsula) and the larger-scale Asaila depression near the western coast are studied in order to put archaeological discoveries into a wider environmental context. Geomorphic mapping of the Asaila basin shows a much greater geomorphic variability than documented in literature so far with relict signs of surface runoff. An 8 m long sediment core taken in the sabkha-type sand flats of the western basin reveals a continuous dominance of aeolian morphodynamics during the early to mid-Holocene. Mounds preserved by evaporite horizons representing capillarites originally grown in the vadose zone are a clear sign of groundwater-level drop after the sea-level highstand ca. 6000–4500 years ago. Deflation followed the lowering of the Stokes surface, leaving mounds where the relict capillarites were able to fixate and preserve the palaeo-surface. Abundant archaeological evidence of Early and Middle Neolithic occupation – the latter with a clear focus inside the central Asaila basin – indicate more favourable living conditions than today. In contrast, the sediment record of the investigated *riyad* in the south is very shallow, younger and controlled by surface discharge, deflation and the constantly diminishing barchan dune cover in Qatar over the Middle and Late Holocene. The young age of the infill (ca. 1500 to 2000 years) explains the absence of findings older than the Late Islamic period. Indicators of current net deflation may relate to a decrease in surface runoff and sediment supply only in recent decades to centuries. In the future, geophysical prospection of the *riyad* may help to locate thicker sedimentary archives and the analysis of grain size distribution, micromorphology, phytoliths or even pollen spectra may enhance our understanding of the interplay of regional environmental changes and cultural history.

Kurzfassung: Die systematische archäologische Erkundung des Südens der katarischen Halbinsel begann in den 1950er Jahren. Lokale und regionale Daten zu den die regionale Kulturentwicklung begleitenden klimatischen Schwankungen und Landschaftsveränderungen im Holozän fehlen allerdings weitgehend. Dieser Beitrag liefert einen Überblick über die geomorphologische Variabilität des südlichen Teils von Katar mit einem Schwerpunkt auf karstbürtigen Hohlformen, deren verhältnismäßig reiches archäologisches Erbe bis in das Paläolithikum(?)/Frühe Neolithikum zurückreicht. Basierend auf einer detaillierten geomorphologischen Kartierkampagne, Sedimentkernen und Altersdatierung mit Hilfe optisch stimulierter Lumineszenz erfolgt eine Rekonstruktion der Sedimentationsgeschichte der räumlich bedeutenden *Riyad* (Singular: *Rawdha*; flache, kleinskalige, sedimentgefüllte Karsthohlformen) und des größeren Beckens von Asaila in der Nähe der Westküste, um die während der vergangenen Dekaden getätigten archäologischen Funde und Erkenntnisse in einen erweiterten Umweltkontext einzuordnen. Die geomorphologische Kartierung des Asaila-Beckens zeigt eine weit größere Variabilität an Oberflächenformen als bisher in der Literatur dokumentiert, darunter auch deutliche Indikatoren für reliktischen Oberflächenabfluss. Während der 8 m lange Sedimentkern aus dem sabkhaähnlichen Bereich des westlichen Beckens eine kontinuierliche Dominanz der äolischen Morphodynamik über das frühe bis mittlere Holozän andeutet, sind die von kleinen hügelartigen Formen dominierten Bereiche durch reliktische, einst in der vadosen Zone gewachsene kapillare Evaporithorizonte fixiert worden. Dies ist ein deutliches Zeichen für vorherrschende Deflation seit dem Hochstand des Meeresspiegels (und des Grundwasserspiegels) vor ca. 6000–4500 Jahren. Zahlreiche früh- und mittelneolithische Streufunde – letztere mit einem klaren Schwerpunkt im zentralen Asaila-Becken – weisen auf günstigere Lebensbedingungen zu dieser Phase hin. Die sedimentäre Füllung der untersuchten *Riyad* ist deutlich flacher und jünger und wird durch Oberflächenabfluss, Deflation und die sukzessiv abnehmende Barchan-Dünenbedeckung in Katar während des Mittel- und Spätholozäns determiniert. Das junge Alter der Füllung (ca. 1500–2000 Jahre) erklärt das Fehlen archäologischer Funde, die älter als spätislamisch datieren. Indikatoren aktuell dominierender Deflation (lineare Korrasionsrillen, Mikro-Yardangs) sind mögliche Hinweise auf einen Rückgang von Oberflächenabfluss und Sedimenteintrag innerhalb der letzten Jahrzehnte bis wenigen Jahrhunderte. Eine geophysikalische Prospektion der *Riyad*, die die Lokalisierung möglichst mächtiger Sedimentpakete erlauben würde, in Kombination mit der Analyse von Korngrößenverteilung, Mikromorphologie, Phytolithen oder gar Pollenspektren, könnte in Zukunft Teil einer Strategie sein, hier detailliertere Daten zur Paläo-Umweltdynamik der zentralen Bereiche Katars zu generieren.

1 Introduction

Pioneering archaeological surveys and excavations in Qatar started more than 60 years ago (e.g. Glob, 1958; Kapel, 1967; de Cardi, 1978; Tixier, 1980; Inizan, 1988). During the last decade, these were supplemented by intensified interdisciplinary research on all phases of the peninsula's cultural heritage (e.g. Al-Naimi et al., 2011; Rees et al., 2011; Cuttler and Al-Naimi, 2013; Eichmann et al., 2014; Gerber et al., 2014; Drechsler, 2014; Drechsler et al., 2013, 2016; Izquierdo Zamora et al., 2015; McPhillips et al., 2015). While evidence for the Palaeolithic remains under debate (Glob, 1958; Kapel, 1967; Al-Naimi et al., 2010; Cuttler and Al-Naimi, 2013; Scott-Jackson et al., 2015; Drechsler, 2014; Drechsler et al., 2016), Early and Middle Neolithic flint scatters along with burial cairns at a number of locations testify the occurrence of mobile to semi-stationary groups at that time (Drechsler et al., 2016). The Early Neolithic mainly comprises Qatar-B sites sensu Kapel (1967) and Inizan (1988), tentatively dated to the 7th millennium BCE. The Middle Neolithic is often represented by surface finds of tile knives, scrapers, bifacial arrowheads and, in some cases, Ubaid-style pottery (Tixier, 1980; Inizan, 1988; Drechsler, 2014), which implies links with other Ubaid-related sites of the southern Arabian Gulf coast dated to the 6th–5th millennium BCE (Oates, 1978; Uerpmann and Uerpmann, 1996; Kainert and Drechsler, 2014). The earliest known settlement of Qatar was identified in Wadi Debayān at the northwest coast, dating back 7500 years (Al-Naimi et al., 2011; Tetlow et al., 2013). Of similar age are the fishermen's huts near Shagra at the east coast, which were associated with the Ubaid period by Inizan (1988). The decline of the Ubaid culture marked the onset of a period represented by very few cultural remains in Qatar, coinciding with the "Dark Millennium" as defined for the southeastern gulf shores (Uerpmann, 2003; Preston et al., 2012; Muhesen and Al-Naimi, 2014). The Bronze Age is only sparsely represented in Qatar, most prominently in the form of pottery and a purple-dye industry at Al-Khor north of Doha (Edens, 1999; Carter and Killick, 2010). Such finds are nearly absent in the southern part of the country (Gerber et al., 2014). Burial cairns are distributed over the entire peninsula and mostly from the Iron Age (ca. 300 BCE–300 CE) (Bibby, 1965; Buckley, 1973; Konishi et al., 1988), even though some of them have recently been dated to as old as the Ubaid period (Cuttler et al., 2013; Izquierdo Zamora et al., 2015). No evidence exists for Iron Age settlements, but a coexistence of nomadic pastoralism and sedentary lifestyles has been postulated (Muhasen and Al-Naimi, 2014). Permanent settlements emerged around the 8th century CE (Abbasid period), in particular along the northwestern coast (Guérin and Al-Naimi, 2009; Macumber, 2015). The nomadic and semi-nomadic Bedouin culture, however, coexisted and persisted well into the 20th century CE, focussing on the shallow karst depressions of the Qatar peninsula as campsites (McPhillips et al., 2015).

Underpinning research on the concomitant environmental changes is clearly in its infancy, consisting mainly of the outcome of the QNHER (Qatar National Historic Environment Record) project covering the northern part of the peninsula (e.g. Cuttler et al., 2011; Cuttler and Al-Naimi, 2013; Macumber, 2011, 2015; Tetlow et al., 2013). Isolated contributions to the framework of earlier archaeological missions mainly focus on Late Quaternary coastal changes and are rather preliminary (Vita-Finzi, 1978; Perthuisot, 1980). Thus, when the South Qatar Survey Project (SQSP) started in late 2012 as a joint operation between Qatar Museums and the Orient Department of the German Archaeological Institute, little well-established information existed regarding dynamics of vegetation, water availability and landforms. In the course of the archaeological survey, shallow, sediment-filled karst depressions referred to as *riyad* (singular *rawdha* or *rawdah*) (Batanouny, 1981; Babikir, 1986; Sadiq and Nasir, 2002; Al-Yousef, 2003; Macumber, 2011, 2015) turned out to be focal points of historic occupation, in contrast with the barren surrounding hamada (Eichmann et al., 2014; Gerber et al., 2014; Pfeiffer, 2015). A second priority of the SQSP was assigned to the large depression of Asaila in central-western Qatar (locally referred to as Jaow Al Bahath), which, compared to the rest of Qatar, preserves a high concentration of Early and Middle Neolithic single flint artefacts and flint artefact scatters, along with numerous findings of the pre-Islamic, Islamic and Modern periods (Kapel, 1967; Inizan, 1988; Pelegrin and Inizan, 2013; Drechsler, 2014; Drechsler et al., 2016).

This paper provides a general overview of the variability of geomorphic environments of southern Qatar (defined here as the part of the peninsula south of the Dukhan road; Fig. 1) over Holocene timescales. Based on a detailed geomorphic mapping campaign, sediment cores and optically stimulated luminescence (OSL) data, the dynamics of *riyad* and the basins of Asaila and adjacent Jaow Aqeeq (Fig. 1) are evaluated in order to put the Early Neolithic to Islamic archaeological discoveries of the SQSP (Drechsler, 2014; Drechsler et al., 2016; Eichmann et al., 2014; Gerber et al., 2014; Pfeiffer, 2015) into a wider environmental context.

2 The physical setting of southern Qatar

2.1 Geology and tectonic setting

The Qatar peninsula protrudes from the Arabian Peninsula into the Arabian Gulf. It represents an anticlinal structure of uplifted Palaeocene to Middle Eocene limestones, dolomites, marls, chalks and shales, intercalated with evaporites (Fig. 1). Lower and Middle Eocene carbonates comprise 80 % (Rus Formation ~ 10 %; Dammam Formation $\sim$ 70 %) of Qatar's surface (Al-Yousef, 2003; Al-Saad, 2005). Miocene units are mainly found in southern Qatar, represented by the Dam and Hofuf formations. The Dam Formation consists of a sequence of shallow marine limestone, gypsum, dolomite and mud, whereas the Hofuf Formation also contains continental conglomerates with a matrix of aeolian sand and gypsum (Cavelier, 1970; Al-Yousef, 2003).

The topography is dominated by the central N–S-trending Qatar Anticline, which has been driven by tectonic uplift since the Palaeogene and created smaller anticlinal and dome structures. The Dukhan Anticline (NNW–SSE) in the west is another major structural feature, bearing the largest oil reservoirs of the area, creating a steeper surface relief than the Qatar Anticline and causing slight tilting of the entire limestone sequence (Al-Yousef, 2003).

2.2 Terrestrial geomorphic environments

2.2.1 Hamadas

Notable topographic elevations occur only in the south, reaching 103 m a.s.l. (above mean sea level) at the highest point. The majority of the peninsula is flat and the most widespread landform is hamadas (Fig. S8 in the Supple-

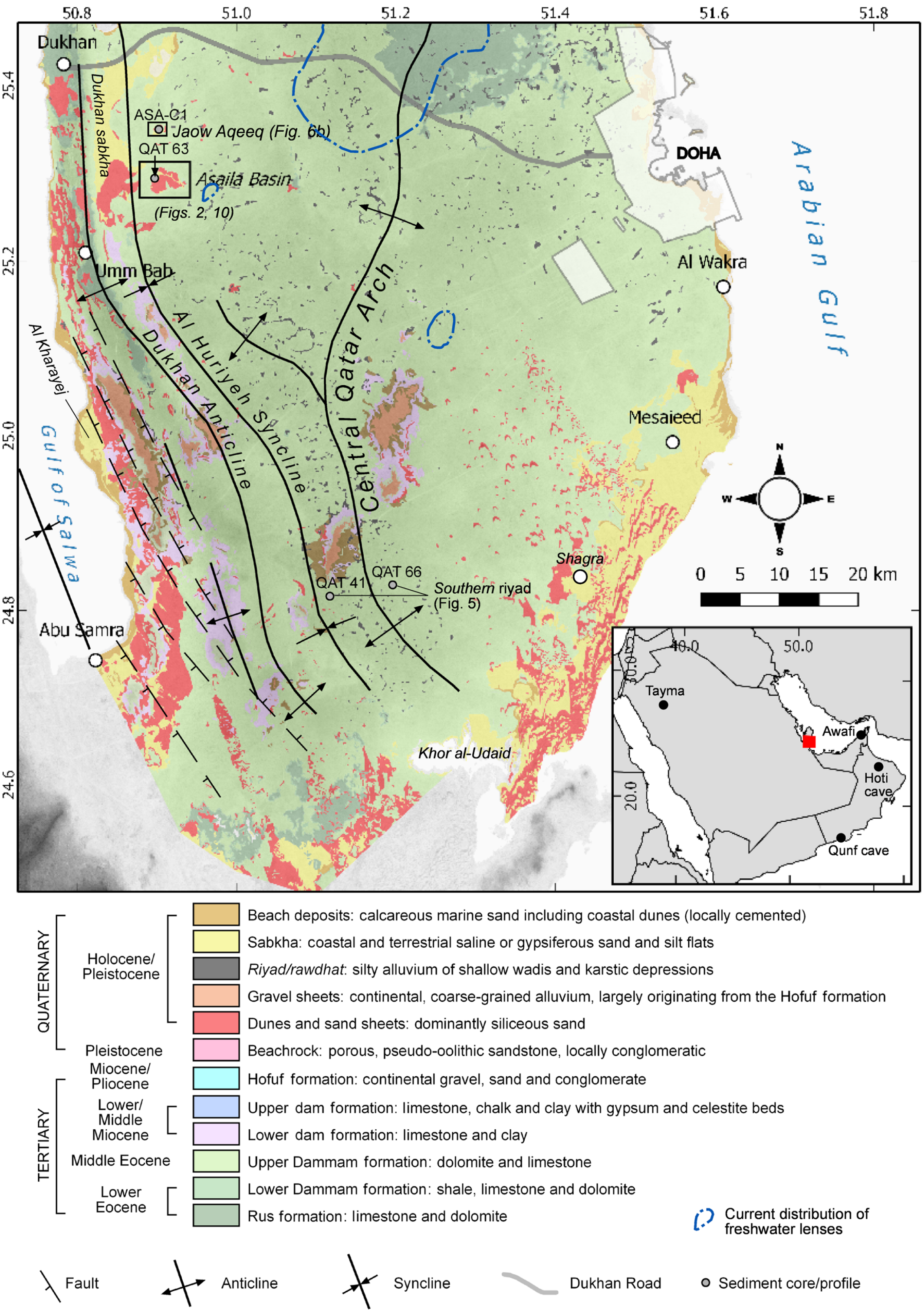

Figure 1. Geological map of southern Qatar based on the national geological map of 1980 (State of Qatar, 1980), overlying an ASTER global digital elevation model, which is a product of the US Ministry of Trade and Economy (METI) and the National Aeronautics and Space Administration (NASA). The main study area of the Asaila basin as well as coring sites in the Jaow Aqeeq basin further north (ASA-C1) and the southern *riyad* are depicted (QAT 41, QAT 66). Tectonic features are adapted from Al-Yousef (2003). The distribution of freshwater conditions in groundwater, which, depending on different sources, may have an upper limit of total dissolved solids of 3000 ppm (e.g. Heberger and Donnelly, 2015), are based on data of the Qatar Department of Environment, cited in Macumber (2012). The overview map indicates the location of the main map and palaeoclimate records referred to in the text.

ment), locally referred to as *hazm* (very gently sloping) or *mistah* (entirely flat), i.e. stone pavements covering most of the Dammam limestone province (Fig. 1) (Perthuisot, 1980; Batanouny, 1981). These plains are covered by mostly angular, in situ limestone gravel (see Benazzouz, 2004; Goudie, 2004b). Vegetation cover of the hamadas is very scarce; only isolated xerophile shrubs and trees such as *Tetraena qatarense*, *Acacia tortilis* or *Lycium shawii* are found between the surface stones (Batanouny, 1981).

2.2.2 Rocky ridges

Rocky ridges of southern Qatar relate to the N–S-trending anticlines, in particular to the Miocene Dam Formation along the southwest coast between Dukhan and south of Umm Bab (Fig. 1). They form mesas and buttes, controlled by varying resistivity of carbonate strata and reg surfaces, i.e. pavements of smaller, par-autochthonous clasts (see Benazzouz, 2004). Patchy sand accumulations in depressions of the rocky ridges are the only sites where sparse vegetation is found today, consisting mainly of *Panicum turgidum* and *Zygophyllum qatarense* (Fig. S14) (Batanouny, 1981).

2.2.3 Karst depressions

The term *rawdha* (Arabic "garden") refers to the fine-grained infill of shallow, round, slightly elongated or more irregular (e.g. when coalesced) inland depressions of 100 m up to a few kilometres in diameter. *Riyad* result from solution and collapse of the Eocene Rus and Dammam gypsum and limestone and are most abundant in the central part of the peninsula (Fig. 1). Their formation is related to the presence and orientation of anticlinal joints and fractures and, as hypothesized by Sadiq and Nasir (2002), to intensified karstification during the wetter Middle Pleistocene. *Riyad* sediments usually consist of light brown silty fine sand provided by sheet floods; carbonate and salt contents are low (Babikir, 1986). Usually they are topped by thin drapes of coarse aeolian sand or even nebkhas – mounds of aeolian sediment trapped and fixated by shrubs (Goudie, 2004a) – of up to 2 m height (Perthuisot, 1980; Macumber, 2011; Engel and Brückner, 2014). Most *riyad* are currently subject to deflation as indicated by micro-yardangs and linear corrasion features at the surface (Engel et al., 2018; Figs. S32, S33). The *riyad* of Qatar's interior provide evidence for occupation indicated by a considerable amount of pottery of different wares mostly dating into the (Late) Islamic and Modern periods. Stone structures of temporary character reflecting the presence of Bedouins are abundant (Eichmann et al., 2014; Gerber et al., 2014). The widest and deepest depressions of southern Qatar, significantly exceeding the dimensions of *riyad*, are the Asaila basin ("Acila depression" in Inizan, 1988; Macumber, 2012; Pelegrin and Inizan, 2013; local name is Jaow al Bahath), separated from the Dukhan continental sabkha by a massive limestone ridge, and the Jaow Aqeeq basin (Fig. 1). Both depressions result from collapse and solution over major faults and joint-flow drainage estimated to be active at least since the Miocene. Sadiq and Nasir (2002) suggest a genetic sequence reaching from deepening and widening cylindrical karst pits, which coalesce subterraneously (compound karst pits) and develop larger bottle- and bowl-shape karst pits through collapse processes. These pits gradually fill up with predominantly aeolian deposits to form such mature depressions or basins.

2.2.4 Wadis

Wadis are most prominent in the southwest of Qatar, where they accumulate some silt and clay and are intercalated by gravel sheets, which result from episodic rainfall events. The wadis show a relatively dense vegetation cover characterized by *Pennisetum divisum*, *Acacia ehrenbergiana*, *L. shawii* and, where aeolian dynamics increase, *Leptadenia pyrotechnica* (Batanouny, 1981).

2.2.5 Coastal sabkhas

The low-lying coastlines of Qatar support the formation of coastal sabkhas, i.e. saline flats in intertidal position. Coastal sabkhas are extensive in the southeast, around Khor al-Udaid, and are characterized by temporary flooding, a water table close to the surface and the precipitation of evaporites within the sediment column and on the surface. A large continental sabkha without surface connection to the sea is formed in the synclinal depression east of the Dukhan Ridge. Its lowest point is 6 m below sea level (Al-Yousef, 2003). The coastal sabkhas are Holocene features mostly resulting from coastal progradation along the entire Qatari coast following the mid-Holocene sea-level highstand (e.g. Billeaud et al., 2014; Strohmenger and Jameson, 2018). Coastal sabkhas with fine-grained soil may host halophile vegetation such as *Arthrocnemum glaucum*, *Juncus rigidus* or *Aeluropus lagopoides*. Where they merge into tidal flats not bordered by beach ridges, mangroves of *Avicennia* may establish (Batanouny, 1981).

2.2.6 Barchan dunes

In addition to the sand deposits found along the rocky ridges of southwestern Qatar, aeolian processes formed barchan dune fields in the southeast. The availability of quartz sand as source material and the regional Shamal wind system approaching from NW to NNW are the defining factors (Embabi and Ashour, 1993; Rao et al., 2001; Al Senafi and Anis, 2015). Once having crossed and covered the peninsula from NNW to SSE, the sediment source area towards the inner gulf became cut off due to the Holocene marine transgression into the Arabian Gulf, just before the mid-Holocene sea-level highstand. The southeastern dune population migrating with a speed of several metres per year represents a relict landform constantly diminishing in size as the dunes "calve" into the Arabian Gulf (Engel et al., 2018). While the barchan dunes themselves are free of vegetation, *Cyperus conglomeratus* may establish along their margins (Batanouny, 1981).

2.3 Present and former climate

The present climate of Qatar is arid, though the relative humidity may rise up to 90 %. Annual rainfall amounts to 50–80 mm and mainly occurs during winter and spring. However, the spatio-temporal pattern of rainfall is highly irregular (Embabi and Ashour, 1993). The NW-to-NNW Shamal winds are active mostly during early June to mid-July and November to March (Rao et al., 2001; Al-Yousef, 2003; Al Senafi and Anis, 2015), and they drive aeolian morphodynamics throughout the peninsula (Embabi and Ashour, 1993; Engel et al., 2018).

Climate as the dominant factor shaping the physical landscape, controlling water availability and influencing occupation patterns of Qatar, has varied in the past. During glacial–interglacial cycles, and even on millennial timescales over the Holocene, geological records from different parts of the Arabian Peninsula indicate considerable fluctuations (e.g. Fleitmann et al., 2007; Engel et al., 2012, 2017; Preston et al., 2012; Dinies et al., 2015, 2016; Guagnin et al., 2016; Parker et al., 2016, Breeze et al., 2017; Parton et al., 2018). The closest palaeoclimate record on the Arabian Peninsula is located at Ras al-Khaimah, UAE (Preston et al., 2012; Parker et al., 2016), where lake deposits reflecting a rainfall surplus date between 9.0–8.3 and 3.0 ka cal BP. The only reference presenting local Late Quaternary rainfall variability of Qatar describes humid conditions during the Last Glacial Maximum 20 kyr ago and increasing aridity towards the present with a short humid deviation during the mid-Holocene. However, this curve has to be considered with caution since no specific data source is provided (Perthuisot, 1980).

As recharge rates are low, permanent freshwater bodies are absent. Easily accessible, potable groundwater aquifers representing the main limiting factor of ancient settlement activity are rare. Most freshwater aquifers occur in the north, while in the south they are very local and isolated (Fig. 1). Groundwater tables at the coast tend to incline towards the sea level. According to Macumber (2011, 2015), the Asaila depression is one of the few sites with relatively easy access to shallow fresh to slightly brackish groundwater in the south of Qatar.

3 Methods

This study is based on work carried out at the Asaila basin, the basin of Jaow Aqeeq and two specific *riyad* in the southern part of the peninsula (Fig. 1). At Asaila, we conducted a detailed geomorphic mapping campaign, carried out a magnetometer prospection and took an 8 m long sediment core (QAT 63). At Jaow Aqeeq, a 3 m long sediment core (ASA-C1) was taken in order to compare sedimentation patterns inside both basins with different hydrological conditions. The sediment infill of two *riyad* was investigated based on a trench (QAT 41) and a short sediment core (QAT 66).

3.1 Geomorphic mapping

To develop our understanding of past and present geomorphic processes shaping the Asaila depression, a detailed geomorphic mapping campaign was initiated to identify environmental controls of landscape dynamics and explain the spatial distribution of archaeological surface findings. Pre-existing mapping resources included a multispectral IKONOS mosaic from 2004 (resolution $\sim 1\,\mathrm{m\,pixel^{-1}}$), the geological map of Qatar (State of Qatar, 1980), the topographic map of Qatar (State of Qatar, 1971), a predecessor geomorphic map of Inizan (1988) and local geological maps of Al-Yousef (2003), which were used for an initial classification of landforms as polygons in ArcMap v10.3.1. A total of 2 weeks of field mapping in March 2016 included photographic documentation, verification and refinement of the existing documentation. Site location and topographic profiles were realized using a TOPCON Hiper Pro differential global navigation satellite system (DGNSS) with a lateral and vertical error of ±2 cm, a manual GPS and a laser rangefinder (TruPulse 200, Laser Technology Inc.). The resulting map describes (i) geomorphic surface units based on the rock type and type of sediment deposit, (ii) morphodynamics and morphogenesis (aeolian, fluvial, etc.), and (iii) morphometry (slopes, microrelief). Vegetation within the depression was recorded and determined using Batanouny (1981) and Norton et al. (2009).

3.2 Magnetometer prospection

To verify the existence of former surface runoff patterns into the Asaila basin (see geomorphic map in Inizan, 1988) and to localize relict fluvial landforms, a magnetometer prospection was carried out in the area of the Acila 36 excavation (Inizan, 1988; Pelegrin and Inizan, 2013) in the northern part of the basin (Fig. 2). In order to reach the highest possible sensitivity, to realize a time-efficient prospection and to receive additional information on the enrichment of magnetic minerals in lateral sediment layers, we used the Cs total field magnetometer (Scintrex SM4G-Special) using the "duo-sensor" configuration (see examples in Fassbinder, 2015, 2017). Five adjacent grids of 40 m × 40 m were prospected. All details regarding the prospection and data analysis are presented in Supplement Sect. S1.

3.3 Sampling and survey of sediment archives

To study potential changes in depositional environments, which would have had essential implications for the interpretation of the survey findings, a vibracore (QAT 63) was taken in the western part of the Asaila basin using an Atlas Copco Cobra mk1 coring device and open steel probes of 6 and 5 cm

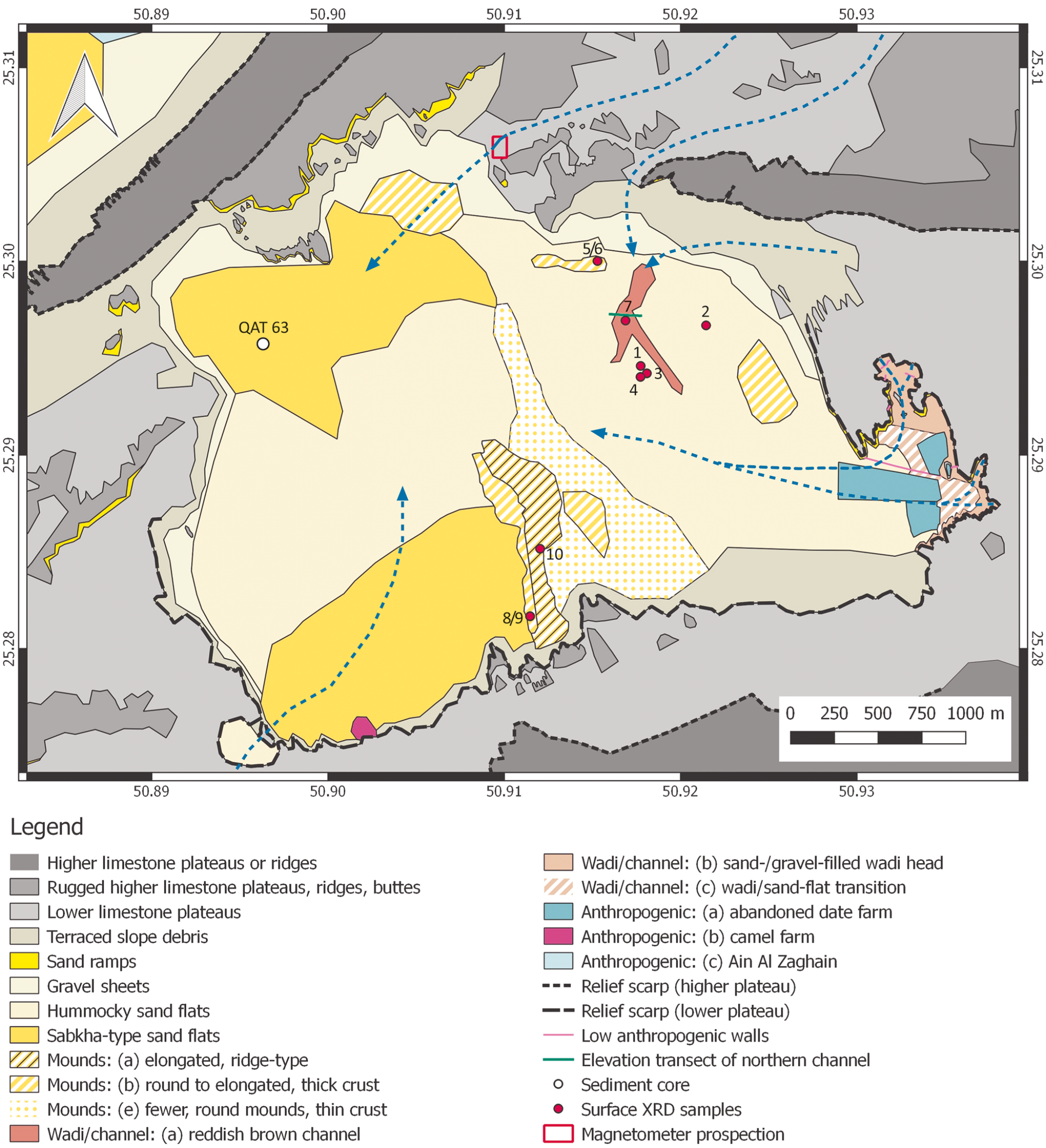

Figure 2. Geomorphic map of the Asaila basin indicating main pathways of surface water inflow (blue arrows; based on Inizan, 1988, and own landform interpretation) as well as the location of the elevation transect across the northern channel (Fig. 5), core QAT 63 (Fig. 6), surface XRD samples (Figs. S5–S7, Table S2) and the magnetogram (Fig. 4).

in diameter. A second shorter core (QAT 63 OSL) was taken at the same site using closed, opaque PVC liners in order to retrieve sample material for optically stimulated luminescence (OSL) dating (Drechsler et al., 2016). For comparison, we extended the analysis of sedimentary archives to the adjacent basin of Jaow Aqeeq, located seaward of the rocky ridge separating the Asaila depression from the Dukhan sabkha. Sediment core (ASA-C1) was taken in the northeastern part of the basin of Jaow Aqeeq (Fig. 1). In order to investigate the formation and dynamics of the key archaeological environments of the *riyad*, many were visited and described during the field surveys between 2012 and 2016, while two of them were studied in more detail using a sediment core (QAT 66) and a trench (QAT 41).

3.4 Sedimentary analyses and dating

3.4.1 Grain size analysis

Due to their overall coarse texture, samples of QAT 63 were analysed for grain size and grain shape by applying dynamic image analysis (Retsch Camsizer P4, particle size range of 30–30 000 µm). Samples from Jaow Aqeeq (ASA-C1) and the *riyad* (QAT 41, QAT 66) were measured using a laser particle analyser (Beckman Coulter LS 13320; particle size range of 0.04–2000 µm) because these had a significant silt component. For analysis of the latter, the pre-treatment procedure includes air-drying of sample material, careful hand pestling and dry-sieving < 1 mm. H_2O_2 (15 %) was added to a < 1 mm aliquot of 0.2–1.0 g in order to remove organic carbon. The sample was washed using a centrifuge until a pH value of 6–8 was reached to avoid neutralization after the addition of 0.5N $Na_4P_2O_7$ (55.7 g L^{-1}) for aggregate dispersion. Calculation of statistical parameters was performed using the GRADISTAT statistic package (Blott and Pye, 2001).

3.4.2 X-ray diffraction analysis

Selected surface samples from the Asaila depression were subjected to X-ray diffraction (XRD) analysis using a Siemens D5000 powder diffractometer (Cu tube) to determine if the landforms are actively formed or of relict nature (active formation may be indicated by the presence of easily soluble evaporites). Samples were measured over a range of 5–75° (2θ) with a step size of 0.05° and a time of 4 s per step (aperture slit = 0.5). The diffractograms were analysed by employing the EVA software package and the ICDD (International Centre for Diffraction Data) database.

3.4.3 OSL dating

Due to a lack of material suitable for radiocarbon dating, age estimates for selected units in the Asaila depression and the *riyad* are derived from OSL dating of sand-sized quartz grains (see Sect. S2 and Figs. S1–S4 for details).

4 Results

4.1 Landforms of the Asaila basin

The Asaila basin has an extent of ca. 12 km^2. It is mostly closed, apart from its western margin, where it is connected with the southwestern extension of the Dukhan sabkha through a series of ridges and small depressions. Detailed field mapping revealed a surprisingly wide range of landform units (Fig. 2; see Sect. S4 for detailed explanations), some of which clearly relate to the former presence of surface water and were probably formed by surface processes during the Holocene.

The basin is framed by the flint-bearing limestone plateaus of the Dammam Formation, consisting of two clear plateau levels, i.e. the higher limestone plateau (ca. 13–18 m Qatar National Datum, QVD), including the rugged higher limestone plateau along its basinward transition (ca. 8–15 m QVD) and the lower limestone plateau (ca. 2–8 m QVD). The higher limestone plateau forms a massive NE–SW-trending structural landform and separates the Asaila basin from the adjacent Dukhan sabkha. Another unit of the higher limestone plateau bounds the basin in the northeast. The transition from the lower limestone plateau to the floor of the Asaila basin occurs quite abruptly in the southwest, south and east, in the form of a vertical step (Fig. 3a). In the north and northwest, the transition is relatively smooth with broad units of terraced slope debris and sand-and-gravel sheets (Figs. 2, 3a). In the northernmost part of the basin, where the lower limestone plateau merges into the gravel sheet, the excavation Acila 36 of Inizan (1988) and Pelegrin and Inizan (2013) is located. At this type site for the Middle Neolithic Qatar-B industries, a new magnetometer prospection was carried out (Fig. S13). Despite poor magnetic susceptibility of the loose sediment cover due to low heavy mineral and iron oxide contents and internal magnetization contrasts of only ±0.8 nT, an unequivocal 10–15 m wide channel structure covered by sand and gravel and running towards the basin can be inferred (Fig. 4). The finding corroborates the assumption of Inizan (1988) of a major inactive surface water trajectory into the basin in this area (Fig. 2). Other geomorphic features reflecting more recent fluvial activity include the following:

i. The first feature is a broad, vegetation-free, linear surface depression of 10–20 cm depth (Fig. 5) with a weak, reddish-brown surface crust of gypsum, quartz sand and calcite (Fig. S6, Table S2) as well as high amounts of clay and silt (Fig. S31). It extends from the central northern margin and bifurcates towards the centre of the basin (Fig. 2).

ii. The second feature is a wadi channel at the eastern end of the Asaila basin, characterized by retrogressive erosion (Figs. S29, S30). The wadi is filled with slope debris and experiences aeolian overprinting in the form of sand ramps (Figs. S12, S29a). However, horizontally bedded platy clasts in a poorly sorted, consolidated sandy matrix and an outwash channel exposing barren bedrock point to at least episodic surface water flows in recent times (Figs. S29a, S30a).

The most extensive landform unit inside the Asaila basin is the hummocky sand flats (Fig. 2), which mostly comprise nebkha fields originating from *Zygophyllum qatarense* shrubs. Some of the nebkhas seem inactive and are protected by thin evaporitic crusts made of gypsum, calcite and minor amounts of sylvine, mixed with quartz sand (samples ASA 1 and 2; Fig. S5, Table S2). In some areas, even halite was present (ASA 3; Fig. S5, Table S2).

Some areas in the central southern, northern and eastern parts are densely covered by characteristic mounds significantly higher than the nebkhas. They are fixated and protected by evaporitic horizons of massive to porous gypsum and minor amounts of calcite and sylvine (samples ASA 5, 6, 8–10; Figs. 3b, S6, S7, Table S2). These mounds vary from perfectly round, up to 1 m high, to narrow, cross-cutting ridges, several tens of metres long (Fig. 3b). Furthermore, large parts inside the basin are covered by vegetation-free sabkha-type sand flats (Fig. 3a, b) with gypsum- and halite-containing surface crusts, in some parts even polygonal structures (Figs. S19, S20).

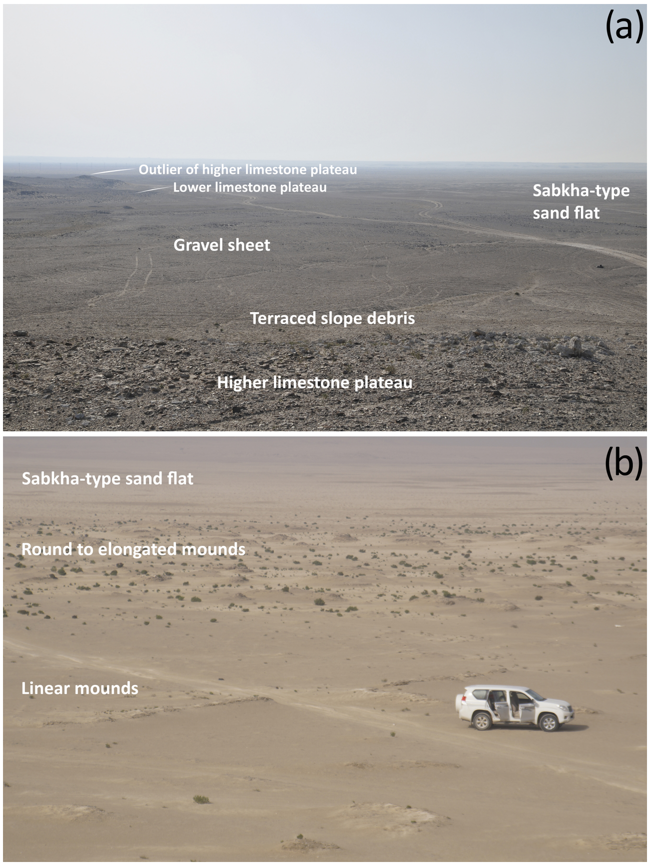

Figure 3. **(a)** View into the Asaila basin from the higher limestone plateau of the NE edge directed towards the east. It shows the terraced slope debris and the gravel sheet merging into the sabkha-type sand flat. In the background, the innermost outlier of the higher limestone plateau is visible, resting on top of the lower limestone plateau. **(b)** View into the basin from an outlier of the rugged higher limestone plateau of the central southern rim directed towards the west. It shows the linear, almost vegetation-free mounds in the foreground, followed by the elongated to round mounds with denser vegetation and the vegetation-less sabkha-type sand flat of the western basin.

4.2 Sedimentary infill of the Asaila depression

Sediment core QAT 63 was taken in the low-lying sabkha-type sand flats of the northwestern Asaila basin (Figs. 2, S21). It reached a depth of 8 m and consists of moderately sorted to moderately well-sorted fine to very fine gravelly medium sand (sensu Blott and Pye, 2001) (Fig. 6). Despite the slight variation in fine, medium and coarse sand, no facies changes occur. Grain size distributions are generally symmetrical to slightly coarsely skewed, apart from samples at 0.58–0.50 m below surface (b.s.) and ca. 1.55–1.40 m b.s., which are very coarsely skewed and poorly sorted. These samples, along with the surface sample, also have the lowest value for grain sphericity and width to length ratio of the entire sequence. A trench next to QAT 63 revealed a massive subsurface gypsum crust at 0.60–0.50 m b.s., while the overlying sands are clearly cross-bedded (Fig. 6b).

Three samples were taken for OSL dating at 0.40 (small trench), 1.90–1.60 and 2.90–2.60 m b.s. (both from core QAT 63 OSL). They reveal coarse-grain (150–200 µm) quartz ages of 5800 ± 300, 6400 ± 300 − −7300 ± 300, and 7500 ± 300 years, respectively (Fig. 6, Table S1). While for the uppermost sample right above the gypsum crust the measured water content of 7 % was used for age calculation, two ages were generated for the sample 1.90–160 m b.s., which is probably located in the vertical fluctuation range of the local groundwater table. The younger age implies a water content of 10 % as measured in the laboratory, the older one assumes water saturation. While fluctuating water contents over time introduce dating uncertainties, the overdispersion of the rather symmetric equivalent dose distributions of 8 %–15 % suggests that incomplete signal resetting is not an issue (Fig. S4).

4.3 The depression of Jaow Aqeeq

Jaow Aqeeq is another larger-scale topographic depression north of Asaila, located close to the coastal sabkha of Dukhan and seaward of the SW–NE-trending limestone ridge separating Asaila from the Dukhan sabkha (Figs. 1, S32). Both depressions share strong geomorphic similarities, even though traces of surface runoff are more prevalent in Jaow Aqeeq compared to Asaila. Outside the depression along its eastern margin, a wide range of archaeological surface finds include fireplaces, clusters of pottery sherds and lithic artefacts (flakes, blade tools, arrowheads), cairns, shells, coins, metal pieces, bulbs of flint, remains of a provisional mosque, and several modern structures. Some of the lithic artefacts may correspond to the Early Neolithic Qatar-B industry, but the context is largely undated. Multiphase utilization of the site is evident. Distinct areas of domestic use and associated lithic workshops (later overprinted by cairns) as well as mosques and modern structures have been mapped (Fig. 7b). The record inside the basin is very poor so far, only consisting of modern garbage (Schönicke et al., 2016). The surface of the inner depression reveals higher moisture and higher abundance of halite- and gypsum-dominated crusts as compared with the Asaila basin.

In order to improve our understanding of the differences between Asaila and nearby Jaow Aqeeq and to evaluate sediment infill, hydrological conditions and palaeoenvironmental changes, sediment core ASA-C1 was taken inside the Jaow Aqeeq depression close to a temporary shallow standing waterbody (Figs. 7, S32). At the surface, the buckled gypsum crust, several centimetres thick and in some places thinly covered by white halite crystals, appeared very similar to sabkhas along the coast of southwest Qatar (e.g. Dukhan sabkha; Al-Yousef, 2003). The groundwater table was located at 35 cm b.s.

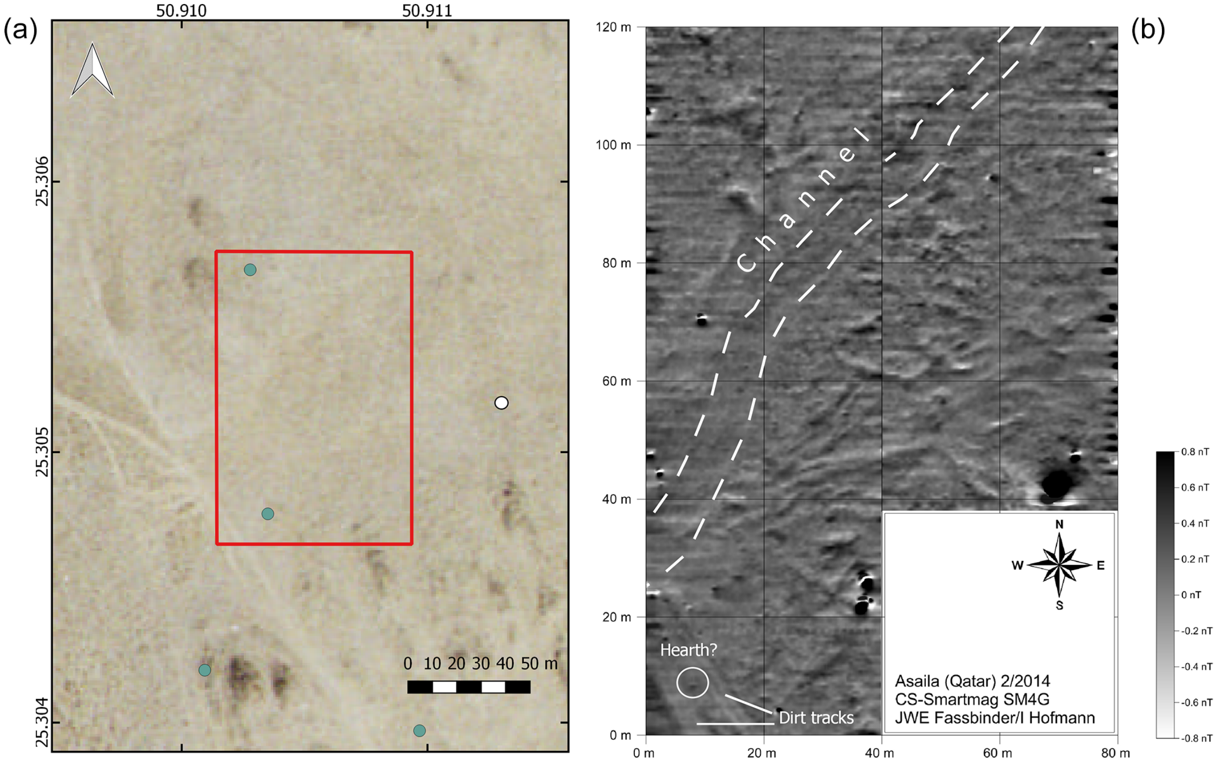

Figure 4. Magnetometer prospection (**b** and red frame in **a**) in the area of the Acila 36 excavation by Inizan (1988), located at the basinward end of the lower limestone plateau (see Fig. 1 for overview). The area, where several scatters of both worked and unworked flint (green dots on **a**) were found during the survey of Drechsler et al. (2016), some also associated with ceramics (white dot), slopes towards the southwest and merges into the sand and gravel sheets and the sabkha-type sand flats of the basin. The magnetogram shows an inactive, subsurface channel structure running towards the basin (white lines).

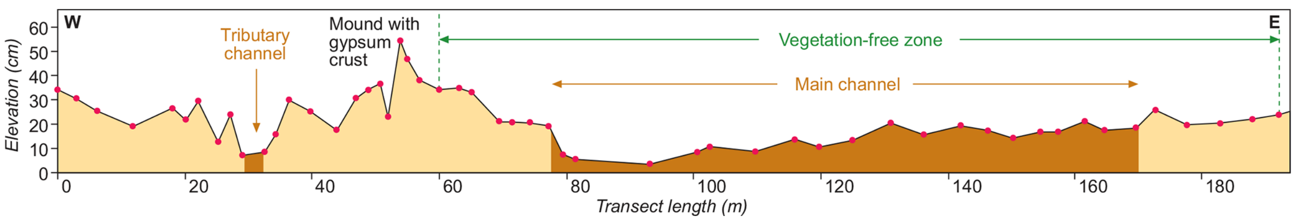

Figure 5. Elevation transect crossing the shallow and wide northern channel (green line in Fig. 2).

The amount of sand varies, while some sections (2.87–2.78, 1.53–1.33, 0.82–0.73 m b.s., uppermost 0.34 m) show a significant clay and silt component of up to 25 % (Fig. 7). The sand mostly consists of well-rounded quartz grains and minor appearances of feldspar, gypsum, reworked Dammam limestone and some dark heavy minerals. The sections with the highest amounts of silt and clay were checked for microfossil indicators for lacustrine environments, but only very isolated, highly abraded skeletal fragments were found. In most cases, the occasional gravel component coincides with large gypsum crystals, which occur in large numbers at several horizons, as either hardgrounds or gypsum mush (ca. 2.30, ca. 1.55, 1.00–0.90 m b.s., upper 20 cm). The sections 1.80–1.53 and 0.73–0.49 m b.s. appear well-stratified with alternating coarser and finer textures. Most sections are moderately sorted to moderately well-sorted, except those containing a more significant silt/clay or gypsum component.

4.4 The southern *riyad*

Two *riyad* were investigated (Fig. 8). At QAT 41 (site HAR 5183/QNHER 5183 in Gerber et al., 2013), a considerable surface relief has formed through wind sculpturing. The loose coarse sand on top is distributed in patches, partly developing wind ripples (Fig. 9b). While smaller limestone pebbles at the surface may result from sheet flood input into the endorheic depression of ca. 0.065 km^2, the small boulders, mostly found along the *rawdha* margins, were brought

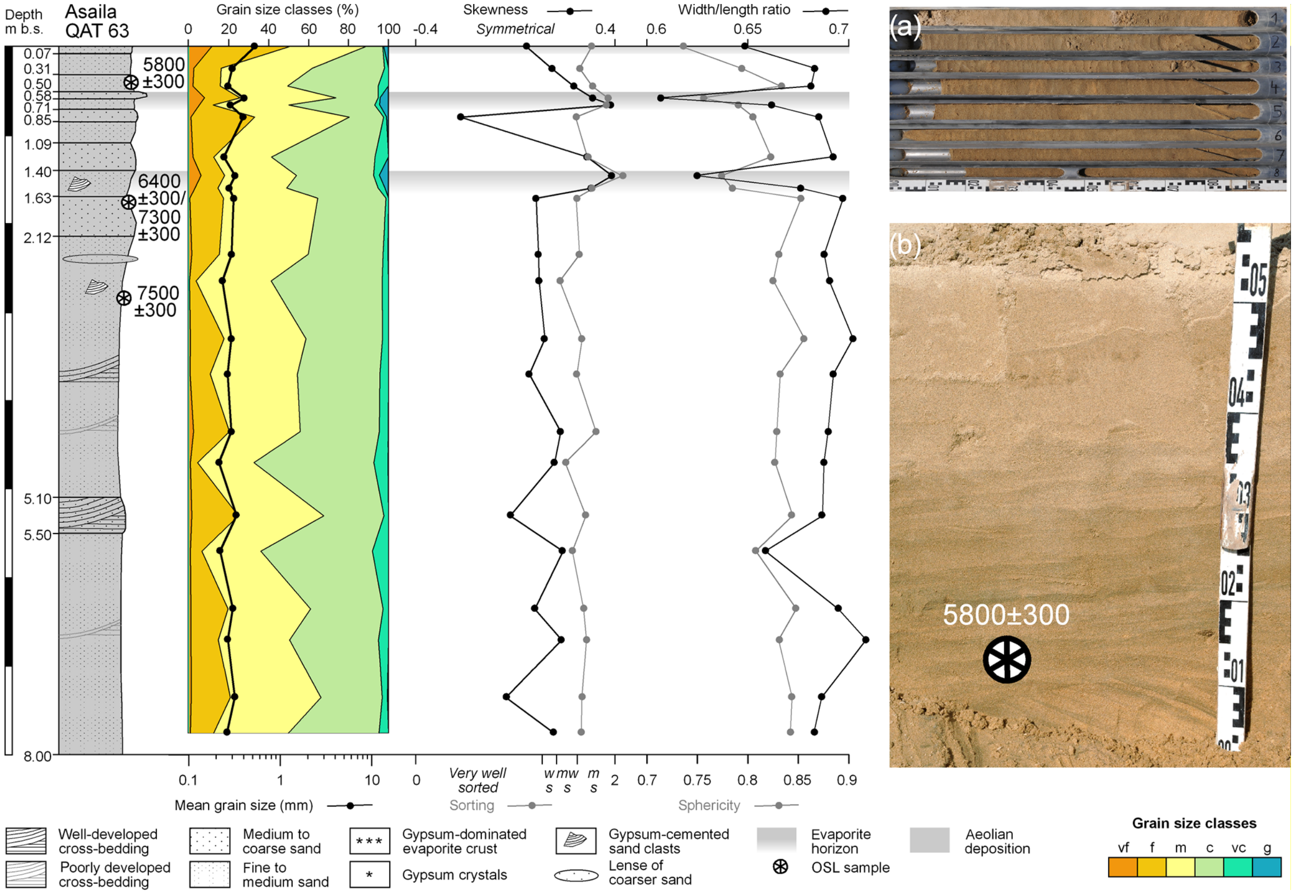

Figure 6. Vibracore QAT 63 from the lowest-lying sabkha-type sand flats of the western Asaila depression (see Fig. 1), showing core log, mean grain size, grain size classes (vf: very fine sand; f: fine sand; m: medium sand; c: coarse sand; vc: very coarse sand; g: gravel), sorting (ws: well-sorted; mws: moderately well-sorted; ms: moderately sorted), skewness, and the width to length ratio and sphericity of the grains (b.s.: below surface). **(a)** The entire core down to a depth of 8 m; **(b)** a close-up of the upper 50 cm of the stratigraphy with the position of the uppermost OSL sample and typical aeolian cross-bedding features (modified after Drechsler et al., 2016).

in by humans to stabilize their tents. Further archaeological findings comprise food remains (shells) (Gerber et al., 2014). A pit dug in the central part revealed only 80 cm of sedimentary infill. Overlying the Dammam limestone is a thin unconsolidated layer of limestone pebbles, up to 3 cm in diameter, in a fine sandy matrix. The section 0.75–0.48 m b.s. shows consolidated, greyish brown medium sand with a minor silt fraction as well as fine to coarse sand (Fig. 10). Furthermore, $CaCO_3$ concretions as pseudomorphs along former root channels were documented. The following layer (0.48–0.42 m b.s.) has a similar sand matrix but contains a greater amount of precipitated $CaCO_3$. The upper unit (0.42–0.00 m b.s.) consists of weakly consolidated silty fine sand with some carbonate concretions and root remains (Fig. 9b).

The two thicker units below and above the $CaCO_3$ horizon reveal OSL dates of 1200 ± 100 (0.60 m b.s.) and 710 ± 30 (0.30 m b.s.) years, respectively (Table S1). Since scatter and shape of equivalent dose distributions suggest relatively complete signal resetting prior to deposition (Fig. S4) and both samples are situated clearly above the groundwater level, the OSL ages provide robust estimates of the time of sediment deposition. Vertical sediment mixing through haloturbation potentially biasing the equivalent dose distributions can be excluded due to negligible salt contents (Babikir, 1986).

Sediment core QAT 66 was taken at the centre of a second, much larger *rawdha* (ca. 0.74 km^2) with a complex system of wadis entering from all sides (Fig. 8). QAT 66 hit bedrock at 0.79 m b.s., exposing an overlying sequence of consolidated, well-sorted, greyish light brown silt with a very small fine-sand component. Downcore changes are negligible. The deposit is compact and entirely dry. It forms an even surface with very sparse and low herbaceous vegetation grazed by goats and sheep. Shrubs trap aeolian sand and form nebkha mounds of > 1 m in elevation (Fig. 9a).

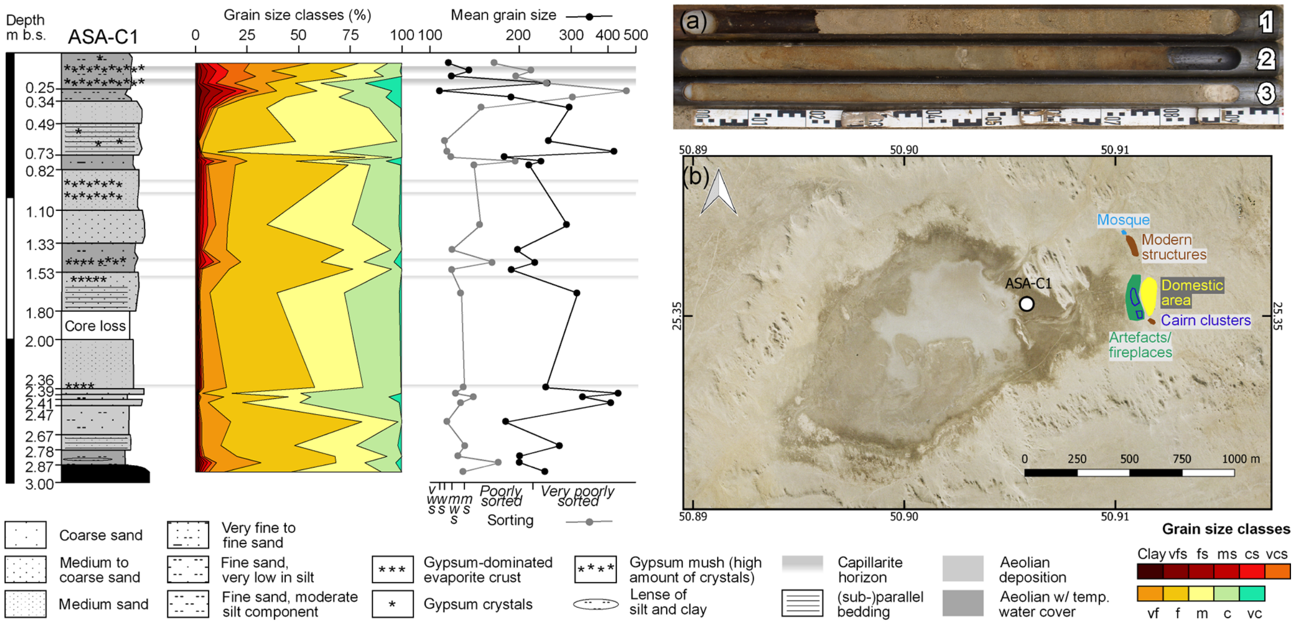

Figure 7. Vibracore ASA-C1 from the large-scale topographical depression of Jaow Aqeeq (Fig. 1), where limestone bedrock was encountered at 2.87 cm b.s. (below surface). Core log, mean grain size, grain size classes (vfs: very fine silt; fs: fine silt; mes: medium silt; cs: coarse silt; vcs: very coarse silt; vf: very fine sand; f: fine sand; m: medium sand; c: coarse sand; vc: very coarse sand) and sorting (vws: very well-sorted; ws: well-sorted; mws: moderately well-sorted; ms: moderately sorted) are shown. **(a)** The entire core down to a depth of 3 m. **(b)** Overview map of Jaow Aqeeq with coring site (basemap is IKONOS image of 2004) and archaeological surface findings according to Schönicke et al. (2016).

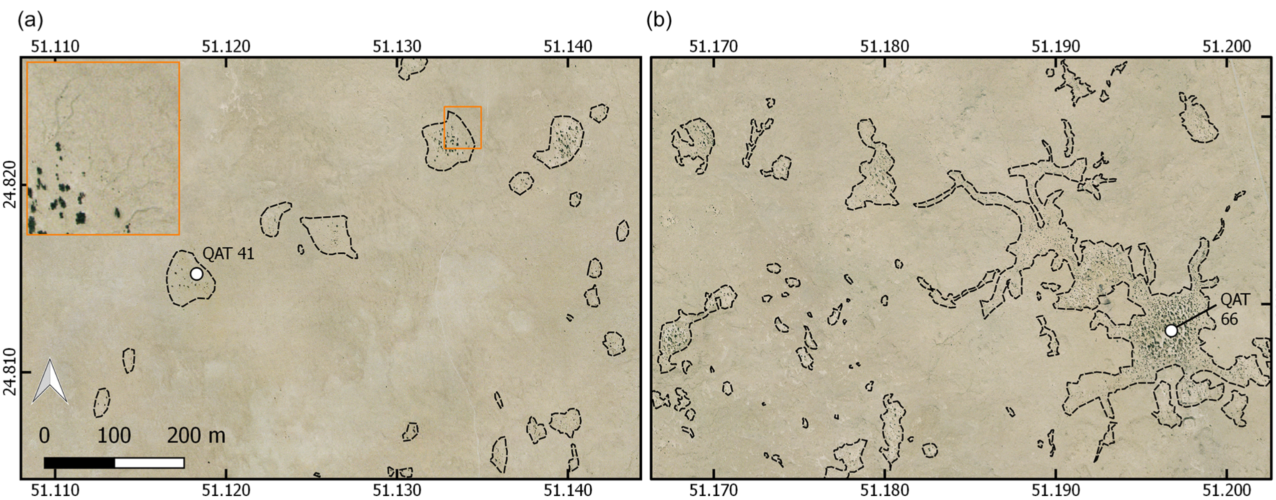

Figure 8. Map of *riyad* in south Qatar (see location in Fig. 1), which were investigated for their sediment infill during the SQSP (based on an IKONOS satellite image of 2004). The outlines of the *riyad* are mostly reflected by vegetation and, where they are more mature as in **(b)**, may develop extended networks of micro-wadis. Note the example of traces of surface discharge into the *riyad* in **(a)** (orange rectangle). QAT 41 represents a trench in *rawdha* HAR 5183 (Gerber et al., 2013) and QAT 66 a sediment core in a *rawdha*, which was not part of the archaeological survey (Fig. 9).

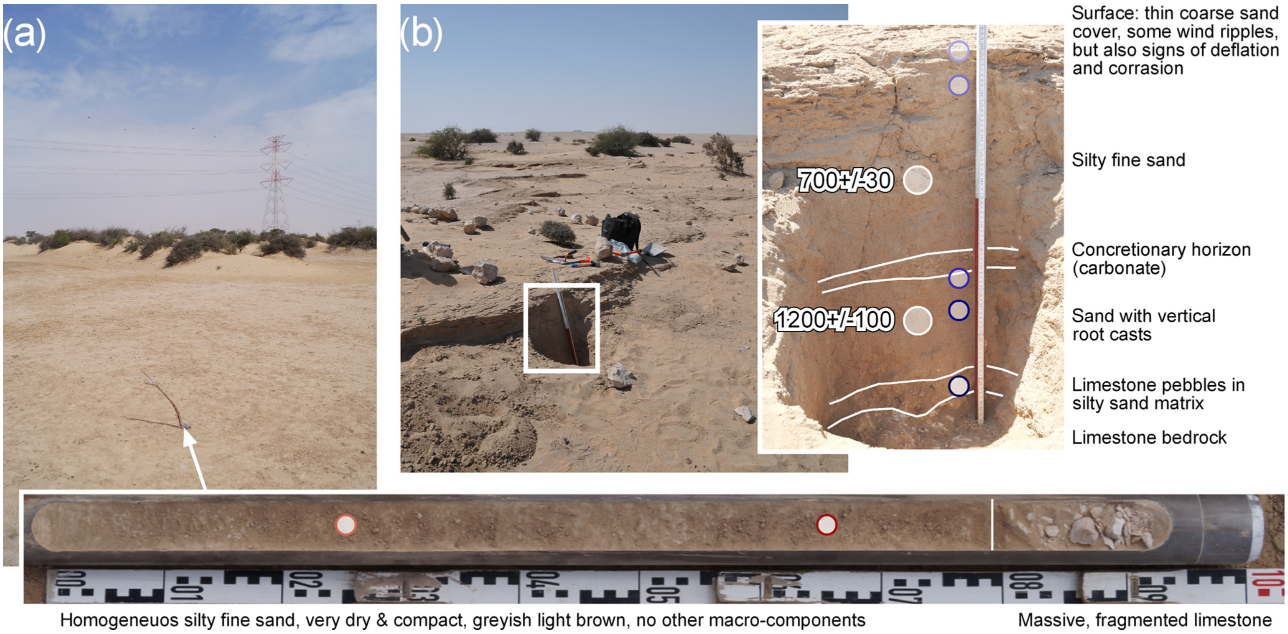

Figure 9. **(a)** Sediment core QAT 66 inside a larger *rawdha* with multiple wadis entering from all sides (Figs. 1, 8); the location of grain size samples is indicated on the core (Fig. 10). **(b)** Profile QAT 41 exposing the sediment infill of a smaller, more elliptic *rawdha* (HAR 5183), with brief stratigraphic log, OSL ages (Table S1) and grain size samples (Fig. 10).

5 Discussion

5.1 Holocene landscape dynamics of the Asaila basin

5.1.1 The geomorphic system

Geomorphic mapping based on field surveys and satellite imagery reveals the polygenetic nature of landforms in the Asaila basin, driven by tectonic, aeolian and fluvial processes as well as subsurface hydrology. The macroscale relief is determined by the roughly N–S-trending anticline or syncline structures, in particular the Al Huriyeh syncline (Fig. 1). The basin's origin may be controlled by a NNE–SSW-striking fault (Inizan, 1988) initiating long-term, subsurface limestone dissolution and collapse since the Miocene (Sadiq and Nasir, 2002) and eventually creating a large-scale morphological depression at the surface. Definite field evidence for such a fault, however, is missing, and other sources emphasize the lack of surface expressions of major faulting on the Qatar peninsula (e.g. Cavalier, 1970; Sadiq and Nasir, 2002).

Surface water exists but is very short-lived and only occurs episodically during strong rainfall. Geomorphic evidence was mapped in the eastern part, in the form of fluvial bedforms in a narrow, shallow channel and a collapsed (sub)surface drainage system, i.e. a potential karst spring. The wadi channel mapped in the central northern part of the basin with its reddish-brown surface appears inactive; halite as a potential sign of recent flooding is absent (sample ASA 7). However, it unequivocally represents a significant pathway of surface runoff into the basin. Another major pathway of surface inflow exists in the northernmost part of the basin, where the higher limestone plateau is dissected in an ENE–WSW orientation (Fig. 2). The small valley entering at the northernmost extension of the basin hosts a subsurface channel morphology (Fig. 4), testifying to the relict nature of more significant surface runoff. There is, however, no evidence for the timing of this increased runoff.

5.1.2 Prevalence of aeolian processes

Grain size measures of sediment core QAT 63 reflect a persisting aeolian environment. OSL data indicate that the sequence captures at least the entire Holocene. Both datasets in combination with present-day sabkha-type surfaces, nebkha formation, sand ripples, streamlined gypsum mounds showing clear signs of corrasion and sand ramps reflecting the main Shamal corridor show that aeolian processes have dominated the Asaila landscape at least since the arrival of humans in the Neolithic. QAT 63 rejects any type of lacustrine environment inside the Asaila basin during that time, which has been speculated by Macumber (2012).

5.1.3 Fluctuations of the groundwater table and capillary evaporite formation

The three horizons of poorly sorted sediments, as well as a lower width to length ratio and sphericity of grains in the uppermost 1.5 m of QAT 63 are related to the ongoing precipitation of mostly gypsum crystals from ascending groundwater in the vadose zone. These processes are similar to

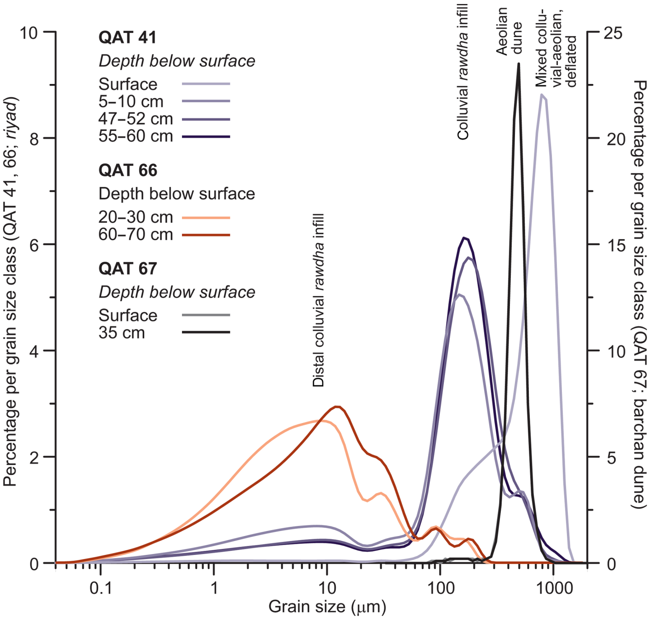

Figure 10. Grain size distribution of samples from the *riyad* (Fig. 9) and, for comparison, a typical barchan dune of south Qatar (QAT 67; curves almost entirely overlap).

those in continental sabkhas, where brines are significantly more highly concentrated (Sonnenfeld and Perthuisot, 1989; Yechieli and Wood, 2002; Ginau et al., 2012). Upward capillary movement from a shallow groundwater table (ca. 1.5 m deep in the Asaila basin today) leads to a halite-dominated and carbonate-containing crust at the surface, underlain by one or several layers of gypsum, also referred to as capillarites (Sonnenfeld and Perthuisot, 1989). This is also reflected by surface XRD samples from the hummocky sand flats, which, similar to the sabkha-type sand flats, represent active equilibrium surfaces of deflation and aeolian deposition. Crust formation is to a large extent driven by capillary rise and the position of the groundwater table. Sample ASA 3 still contains halite, whereas samples ASA 1 and 2 do not contain halite and show how easily salts are deflated and dissolved at the surface (Sonnenfeld and Perthuisot, 1989).

Even though Asaila is located at the southwestern fringe of the freshwater lens of Qatar (Fig. 1), subsurface gypsum dissolution in the Rus and underlying Umm er Radhuma Formations results in elevated levels of salinity and brackish to saline groundwater in the southern peninsula (Lloyd et al., 1987; Macumber, 2011, 2015). Asaila has relatively moderate salinity levels of around 3000 ppm (Macumber, 2012), which is still sufficient to precipitate capillary evaporites in the vadose zone and, in the eastern sabkha-type sand flats, thin buckled gypsum crusts at the surface. However, comparison with the sediment infill and the thick, halite-dominated surface crust at Jaow Aqeeq (ASA-C1) shows how a higher groundwater table and significantly higher groundwater salinity of about 8000 ppm (Macumber, 2012) may lead to more intense precipitation of evaporites in interstitial pore waters and the establishment of inland sabkha conditions. While Jaow Aqeeq seems to directly correspond with the Dukhan coastal sabkha in terms of hydrogeological exchange, the higher limestone plateau separating the Asaila depression from the southeasternmost extension of the Dukhan sabkha is also reflected by the strong SE–NW gradient on the groundwater salinity map in Macumber (2012).

5.1.4 The role of relative sea-level changes in landscape formation

The rate of aeolian sand sedimentation of 1–2 mm yr^{-1} in the upper 3 m of QAT 63 averaged over the time between ca. 7500 and 5800 years ago as inferred from OSL data is driven by two factors: (i) greater sand availability further north (upwind), as large parts of the Qatar peninsula were then still covered by dune fields (Engel et al., 2018), and, (ii) at that time, relative sea level, which is coupled with groundwater levels in low-lying areas near the Qatari coast (Macumber, 2011), rose by several metres (Lambeck, 1996), reaching a highstand around 6000 years ago (Perthuisot, 1977; Engel and Brückner, 2014; Parker et al., 2018; Strohmenger and Jameson, 2018; Rivers et al., 2020). A rising groundwater table and capillary fringe stabilize newly deposited sand in dry climates and lead to net accumulation. Such a raised equilibrium surface close to the shallow groundwater table is referred to as the Stokes surface, below which deflation does not occur due to cohesion of the sediment provided by capillary moisture and initial cementation (Fryberger et al., 1988). It seems that after the sea-level highstand phase (+2–3 m, ca. 6000–4500 years ago; Vita-Finzi, 1978; Cuttler and Al-Naimi, 2013; Engel and Brückner, 2014; Parker et al., 2018; Strohmenger and Jameson, 2018; Rivers et al., 2020), deflation began due to the lowering of the groundwater and the capillary fringe along with sea level, thereby affecting the lowering Stokes surface.

The characteristic mounds covering specific areas of the Asaila basin (Figs. 2, 3a) are mainly preserved by porous, platy or needle-shaped gypsum (surface samples ASA 5, 6, 8–10). We assume that these gypcretes are relict horizons of interstitial gypsum in the vadose zone at the time of the sea-level and groundwater-level highstand. Predominant deflation afterwards in the era of sinking groundwater levels led to the removal of the halite–carbonate surface crust (see Sonnenfeld and Perthuisot, 1989), the aeolian sand below and parts of the more massive gypsum crusts. Where the gypsum withstood erosion, the crust protected the underlying deposits from denudation resulting in the formation of mounds.

5.1.5 Origin of the linear mounds

The origin of the linear mounds (Figs. 2, 3b) in the central southern part of the basin, some of which form irregular grids, remains enigmatic. In some parts, they resemble inverted canals as known from other arid environments, e.g. historical Lower Mesopotamia (Brückner, 2013; Engel and Brückner, 2018) or southern Peru (Beresford-Jones et al., 2009), but no other indication of an anthropogenic origin was found. Alternatively, the network of linear mounds could follow the pattern of subsurface small-scale joints, which provide better conditions for the capillary rise of water to form stable gypsum crusts. Further in-depth investigations are necessary to shed light on the origin of the linear shapes.

5.2 Landscape dynamics and the archaeological record

The limited availability of potable water has always determined ancient settlement patterns in Qatar, explaining why most archaeological sites are located on the northern peninsula. The generally poor groundwater quality in the southern part (Cuttler and Al-Naimi, 2013; Macumber, 2015) meant that Neolithic occupation concentrated mostly around the Asaila basin, where access is fairly easy and the salinity is moderate (Drechsler et al., 2016). Only in recent times have further potentially Palaeolithic and Neolithic sites been discovered closer to the coast (Drechsler, 2014). Several Early Neolithic flint knapping workshops were identified along the margins of the Asaila basin based on the spectrum of single diagnostic Qatar-B artefacts or artefact scatters (dated to ca. 7500–6500 BCE). They existed mostly in direct proximity to outcrops of flint raw material (Pfeiffer, 2015; Drechsler et al., 2016), comprising regular blades from bidirectional naviform cores (Inizan, 1988; Pelegrin and Inizan, 2013). In contrast, Middle Neolithic artefacts, i.e. unifacial and bifacial points, scrapers, and bifacially chipped winged and tanged arrowheads following the "Arabian bifacial lithic tradition" sensu Edens (1982, 1988) (ca. 6500–4500 BCE), show the greatest concentrations inside the basin (Fig. 11). They occur either as scatters of cores, flakes and flint tools in combination with burnt limestone and ashy sediment in the centre of the basin, indicating both in situ flint knapping and domestic activities, or as single tool findings at the lower western margins, where they point to incidental tool usage and discard (Drechsler et al., 2016). Successful refitting of single pieces of the same flint artefacts within a radius of only a few metres inside one of the survey units inside the basin shows that relocation of artefacts is negligible (Schönicke et al., 2016). There appears to have been quite a substantial occupation in the Middle Neolithic with a focus in the centre of the basin, which, at that time, might have provided a higher potential for grazing of both domesticated and wild animals (Drechsler et al., 2016).

Even though no local proxy record of Holocene climatic changes exists in Qatar, the high-resolution δ^{18}O curve from a speleothem at Hoti Cave, Oman (Fleitmann et al., 2007; Fig. 12b), and the palaeo-lacustrine record from Awafi near Ras al-Khaimah, UAE (Parker et al., 2016; Fig. 12d), may provide important references. Both sites received a moisture surplus during Early Holocene to mid-Holocene summer seasons from the Indian Summer Monsoon (Fleitmann et al., 2007) and even more so from the intensified East African Summer Monsoon (EASM) penetrating into the Arabian Peninsula. The role of the mid-level westerlies for the Early Holocene Humid Period (EHHP) in the southeastern Arabian Peninsula, however, remains unclear (Parker et al., 2016). Recent climate model simulations by Jennings et al. (2015) and Guagnin et al. (2016) suggest that Qatar might have had an increase in rainfall following an intensification of the African–Asian monsoonal systems, although far less than the sites of Awafi, Hoti Cave, or another site in south Oman, i.e. Qunf Cave (Fig. 12c). The onset of lacustrine conditions as reflected by the Ti and magnetic susceptibility records from Awafi (Parker et al., 2016; Fig. 12d) overlaps well with the intensification of Middle Neolithic occupation at Asaila (Drechsler et al., 2016; Fig. 12g), which at its later stage also benefitted from the high groundwater table connected to the sea-level highstand (Lambeck, 1996; Parker et al., 2018; Strohmenger and Jameson, 2018; Fig. 12e). The Hoti Cave record indicates an even earlier onset of the EHHP, which may reflect more favourable environmental conditions and incipient human occupation at Asaila already in the Early Neolithic (Fig. 12b, g). The same applies to the northern Arabian palaeolake record from Tayma (Saudi Arabia), which reflects only a very short EHHP and appears offset, probably due to a complex interplay of a range of global and regional atmospheric moisture sources, e.g. the EASM, Mediterranean winter rains and winter–spring tropical plumes (Engel et al., 2012; Enzel et al., 2015; Neugebauer et al., 2018; Parton et al., 2018).

Macumber (2018) associates the phase of a wetter climate around the 6th and 5th millennia BCE with the formation of a massive subterraneous freshwater lens over large parts of Qatar. The subsequent absence of archaeological traces at Asaila – and a reduction of sites in the entire country (Muhesen and Al-Naimi, 2014) as well as across the wider gulf region (Uerpmann, 2003) – is associated with aridification on the eastern and southeastern Arabian Peninsula, sea-level drop and associated groundwater level fall (at least after the highstand plateau ended around 2500 BCE), and the onset of a predominant deflation regime inside the basin. After a hiatus, Islamic (610–1972 CE) to Modern (post 1972 CE) pottery and remains of campsites were found (Figs. 11, 12g), along with cairns on the higher plateau (Gerber et al., 2014; Drechsler et al., 2016), which are difficult to date (Cuttler et al., 2013; Izquierdo Zamora et al., 2015).

5.3 *Rawdha* formation

The uniform sedimentary infill of south Qatar's shallow karst depressions (*riyad*) appears rather young. The one which was dated in this study (QAT 41) has accumulated its silts and sands over the last 2000–1500 years as determined by OSL data. The low ages of the sediment infill explain the absence of older archaeological findings, which, in the *riyad* surveyed

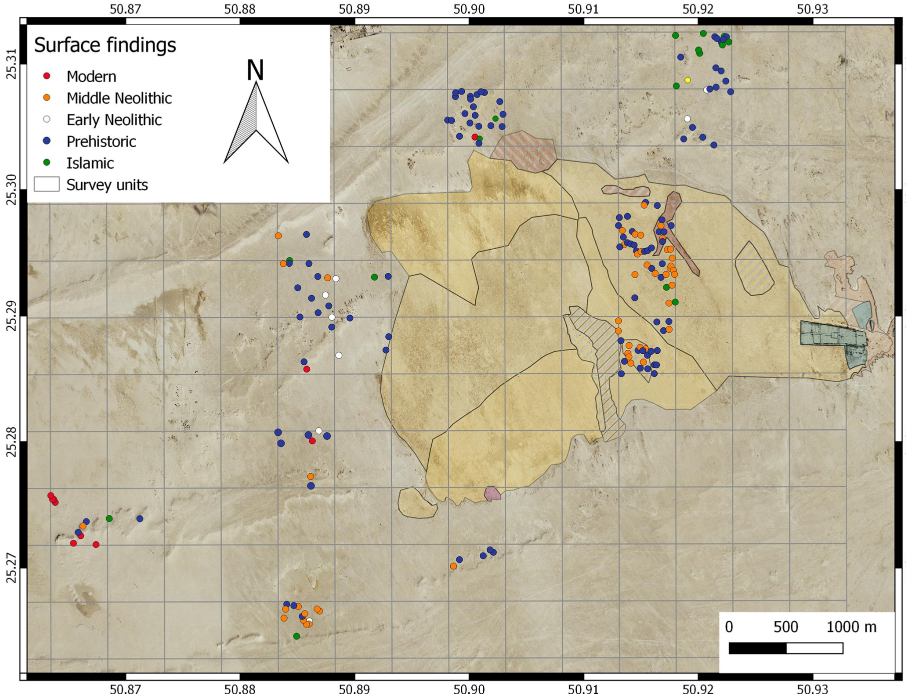

Figure 11. Spatial distribution of archaeological surface findings (basemap from IKONOS 2004) inside and around the Asaila basin. Selected squares (indicated by mapped surface findings) of 500 m × 500 m were surveyed by systematic back-and-forth walking in order to guarantee a 100 % coverage (Drechsler et al., 2016). Geomorphic units of the innermost Asaila basin are shown for orientation (see details in Fig. 2). "Prehistoric" refers to flint artefacts with unspecific character, which, in theory, may date from any period between the Palaeolithic and historical times (Drechsler et al., 2016).

by the SQSP, mainly consist of Late Islamic to Modern period pottery wares, modern trash, Chinese porcelain, coins or temporary mosque structures, all dating to the 18th century CE or younger (Eichmann et al., 2014; Schönicke et al., 2016).

Sedimentation inside the *riyad* is induced by surface runoff events as indicated by small wadi channels and runnels directed towards some of the larger landforms (Macumber, 2015; Fig. 8). The broad grain size distribution, in particular from the distal record inside the large *rawdha* (QAT 66), relates to colluvial processes, even though a contribution of aeolian dust as indicated by geochemical data from *riyad* surfaces of Qatar's interior presented by Yigiterhan et al. (2018) cannot be excluded. As small, endorheic basins, the *riyad* represent pivotal sites of meteoric groundwater recharge (Macumber, 2011, 2015; Cuttler and Naimi, 2013) and groundwater access through wells. They become flooded during rainfall events, which explains the distribution of remains of temporary camps only along their margins (Gerber et al., 2014; Schönicke et al., 2016). Accordingly, the silt component of their infill (Figs. 9, 10) settled out of suspension. Increased soil moisture, strong evaporation and significant sediment contributions of the local limestone-dominated hamada lead to carbonate crust formation in the vadose zone, as observed in QAT 41, and to incipient cementation. The finer grain size spectrum of QAT 66 (Fig. 10) compared to QAT 41 corresponds with its distal location in the centre of a very large *rawdha*.

Thus, net accumulation inside the *riyad* may represent a proxy for surface runoff, which is controlled by rainfall events and, as in our case, by land cover. In the Early Holocene and mid-Holocene, much of Qatar – most probably including the southern *riyad* – was covered and filled by mobile sands. Only after the southeastward migrating barchan dunes, which lost their source due to the transgression of the gulf (Embabi and Ashour, 1993; Engel et al., 2018), had left the *riyad* zone, could fine-grained colluvial deposits accumulate during surface runoff events. The *rawdha* HAR 5183 (QAT 41) is located ca. 21 km upwind of the migrating end of the barchan dunes west of Qatar's inland sea (Khor al-Udaid) (Fig. 1) according to the mean Shamal azimuth of 332° deviation from the north (Embabi and Ashour, 1993). This azimuth seems to have remained stable during the Holocene based on the similar orientation of drowned barchanoid dunes inside the Gulf of Salwa (Al-Hinai et al., 1987). Considering a migration rate of ca. 8–10 m yr^{-1} measured for medium-sized barchan dunes in Qatar over the time span of several decades (Engel et al., 2018), the karst depression became dune-free around ca. 2600–2100 years ago, or even later, if higher migration rates of smaller-sized barchan

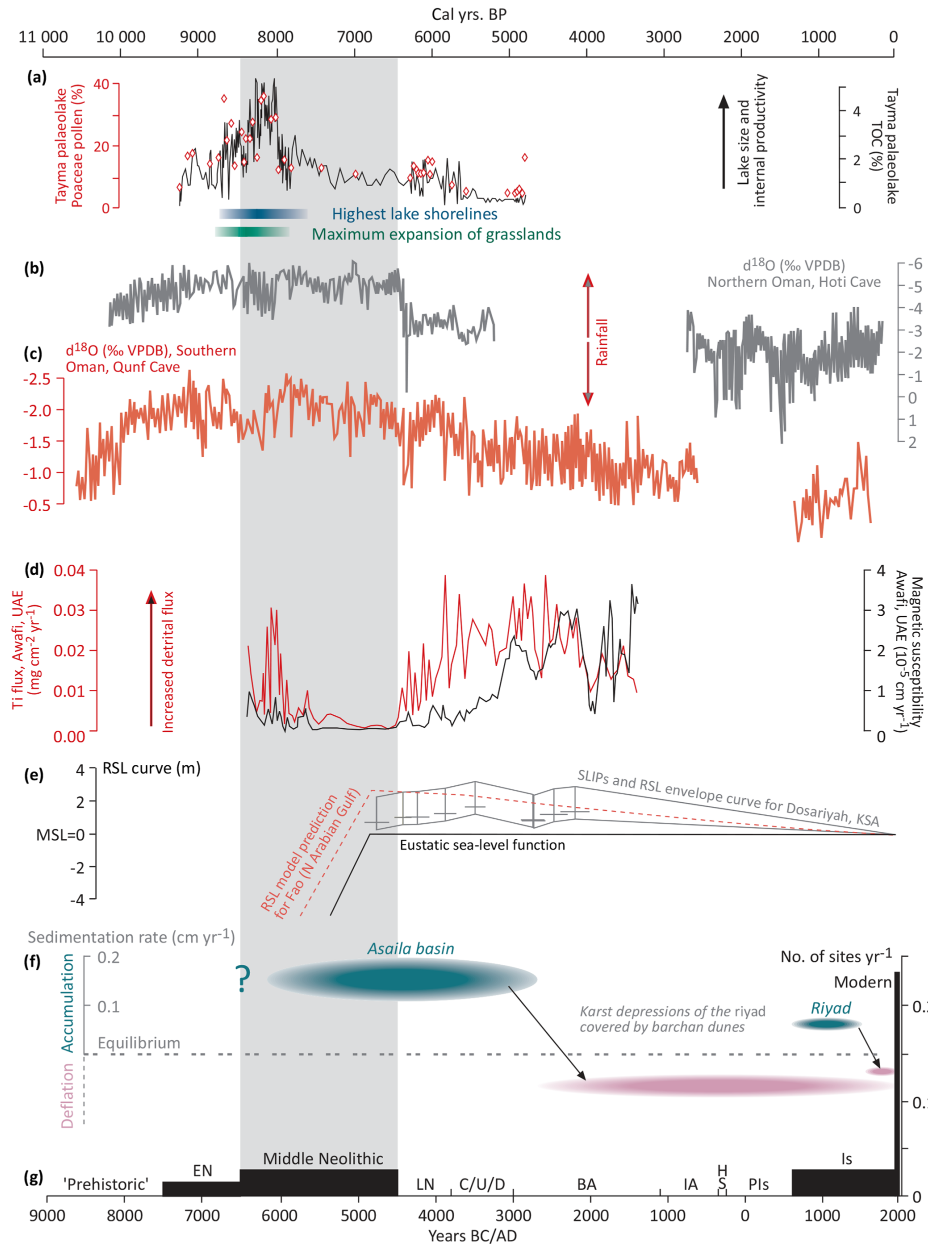

Figure 12. Synopsis of regional palaeoclimate and sea-level data in combination with accumulation–deflation phases in Asaila and the southern *riyad* as well as the chronological density of surface archaeological findings in Asaila. **(a)** TOC (total organic carbon) record and relative abundance of Poaceae pollen (grasses) (Dinies et al., 2016) combined with phases of the highest lake shorelines (Engel et al., 2012, considering revised chronology in Dinies et al., 2015) and maximum grassland expansion (Dinies et al., 2015) from the palaeo-lake and wetlands in the sabkha of Tayma, northern Arabia. Oxygen isotope records of stalagmites from **(b)** Hoti Cave, northern Oman, and **(c)** Qunf Cave, southern Oman (Fleitmann et al., 2007) (VPDB is relative to the Vienna Pee Dee Belemnite standard). **(d)** Ti flux and magnetic susceptibility from the lacustrine record of Awafi, UAE, where low values indicate landscape (dune) stability and higher moisture availability (Parker et al., 2016). **(e)** Envelope curve of relative sea-level stands from Dosariyah, Saudi Arabia, based on ^{14}C-dated sea-level index points considering vertical and lateral error margins (Parker et al., 2018). It is shown in combination with the global eustatic sea-level function and a regional modelled sea-level prediction for the northern head of the Arabian Gulf (Lambeck, 1996), the peak of which is tentatively shifted to account for ^{14}C calibration (MSL is mean sea level). **(f)** Sedimentation rates at Asaila and the southern *riyad* as inferred from OSL data of this study (Figs. 6, 9b, Table S1), and the inferred shift to a deflation regime. Barchan dune cover at *rawdha* QAT 41 was estimated based on migration rates inferred by Engel et al. (2018). Furthermore, the number of sites identified in and around the Asaila basin per year of the time span of each period is shown for the different historical and prehistoric periods (EN: Early Neolithic; MN; Middle Neolithic; LN: Late Neolithic; C: Chalcolithic; U: Uruk; D: Dilmun; BA: Bronze Age; IA: Iron Age; H: Hellenistic; S: Seleucid; PIs: pre-Islamic; Is: Islamic) as a proxy of the intensity of human occupation (Drechsler et al., 2016). The grey vertical bar crossing all proxy data curves emphasizes the Middle Neolithic, which is prominently represented by artefacts inside the Asaila basin (Fig. 11).

dunes are taken into account. This coincides with the start of the runoff-related silt and sand accumulation of the *rawdha* at some point before 1500 years ago, as inferred from OSL data. The archaeological record indicates significant human usage of the *riyad* during the last 300 years, when their infill already resembled today's situation. The only potential climate signal deduced from the surveyed *riyad* so far may be a shift to more pronounced aridity in very recent times indicated by ubiquitous surface deflation patterns and small, decimetre-scale yardangs (Figs. S33, S34). This process may have supported a concentration of young archaeological findings at the surface. Taking these observations into account, it can be concluded that the further north a *rawdha* is located, the longer it has been dune-free, and more time may be represented by its silty sediment record.

6 Conclusions

Among the diverse arid landform units of south Qatar, the Asaila basin as well as the numerous *riyad* of the central peninsula reveal the richest archaeological record. The former has a density of 108 surface findings per square kilometre extrapolated from the three surveyed squares inside the basin (Fig. 11). In contrast to previous maps of the Asaila basin, which only differentiate between "sabkha" and "aeolian deposits" (Al-Yousef, 2003), we demonstrate greater geomorphic variability and additional signs of (relict) surface runoff. The areas of mounds of different shapes – for the first time systematically investigated in this study – are important indicators for groundwater (and, thus, sea level) control of accumulation and deflation inside the basin. While the 8 m long sediment core reveals a continuous dominance of aeolian sedimentation over the Early Holocene to mid-Holocene, the mounds, cemented by capillary evaporites originally grown in the vadose zone, are a clear sign of deflation after the mid-Holocene sea-level (and groundwater-level) highstand. Abundant archaeological evidence of Early and Middle Neolithic occupation – the latter with a clear focus inside the Asaila basin – indicate more favourable living conditions. Whether these imply denser vegetation and better access to groundwater and are linked to the EHHP inferred from other records on the southeastern Arabian Peninsula (e.g. Fleitmann et al., 2007; Preston et al., 2012; Parker et al., 2016) still awaits verification. The existence of more favourable conditions inside the Asaila basin is particularly evident when compared with the adjacent basin of Jaow Aqeeq, which shows how a higher groundwater table and higher groundwater salinity are reflected by higher amounts of capillary gypsum and thicker surface evaporite crusts.

In contrast, the sediment records of the *riyad* in southern Qatar are very shallow, younger (only ca. 1500 years in the case of QAT 41) and apparently controlled by surface runoff, deflation and the constantly diminishing barchan dune cover over the Middle and Late Holocene (see Engel et al., 2018). The young age of the infill explains the exclusive presence of young artefacts, mainly covering the Late Islamic to Modern periods. In combination with the indicators of current deflation, it may relate to a decrease in rainfall and surface runoff in recent decades to centuries. Whether this shift is related to inactivity and burying of runoff channels identified at the northern margin of the Asaila (Figs. 4, 5) is a matter of future investigations. It remains to be stated that the Late Quaternary environmental changes on the peninsula of Qatar are still largely unknown due to a lack of suitable geological archives. This report adds to the scarce information available, e.g. from Wadi Debayān (e.g. Tetlow et al., 2013), northeast Qatar, or the Ras Abrouq peninsula north of Dukhan, where archaeological layers were encountered down to a depth of 2.6 m (Smith, 1978; Vita-Finzi, 1978), even though chronological resolution and climatic significance still need to be improved. In the future, geophysical prospection of the *riyad* further north, e.g. using the combined approach of electrical resistivity tomography and seismic refraction tomography as applied for dolines on Crete by Siart et al. (2010), may help to locate thicker *rawdha* infill with more detailed palaeoenvironmental information through a higher-resolution age model in combination with the analysis of grain size distribution, micromorphology, phytoliths or even pollen spectra.

Data availability. OSL and XRD data are provided in the Supplement file. All grain-size-related data will be provided by the corresponding author upon request.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/egqsj-68-215-2020-supplement.

Author contributions. The study was conceived by ME and HB. The archaeological survey was led by CG, PD, KP and RE. PD provided data on the spatial distribution of archaeological findings in Asaila. Geomorphic mapping was performed by SR, ME, and AP. ME, HB, KP, AP, DW and SR took sediment cores. ME, HB and KP logged and sampled the *rawdha* trenches. JWB conducted the magnetometer prospection and data processing. DB measured luminescence signals and calculated ages. SO conducted XRD measurements and interpreted XRD spectra. ME and DW carried out sedimentological analyses. ME wrote the paper. All authors read, commented on and approved the paper.

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Research article

Archaeological dating of colluvial and lacustrine deposits in a GIS environment investigating the multi-period site Gortz 1 on Oberer Beetzsee, Brandenburg

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Abstract: From the mid-14th century CE onwards, extensive soil erosion, caused by intensive agricultural practices, has led to the destruction of landscape structures in Central Europe. In 2016, the University of Applied Sciences in Berlin investigated the colluvial deposits at the site of Gortz in western Brandenburg (Germany), which had accumulated on the lower slopes and were caused by the processes just mentioned.

The mapping of each individual archaeological find made it possible to project all finds onto one profile running along the slope. Transformation of the finds' coordinates from profile view to plan view enabled the visualization in a Geographical Information System (GIS). The combination of adjacent strata into larger units using a pedological and sedimentological approach enabled an improved dating of colluvial deposits. In addition, the method facilitated the dating of historical water levels in the Beetzsee chain of lakes, which are part of the Havel river system.

As a result, it could be demonstrated that substantial anthropogenic activity, such as clay quarrying and bank straightening, took place during the Late Slavic Period. An interlocking horizon of colluvial and lacustrine deposits indicates that the water level of the lake Oberer Beetzsee rose from a value under 29.4 m above sea level (a.s.l.) in the 11th/12th century CE to approximately 29.8 m a.s.l. in the 13th century CE. However, isolated flooding events during the 13th century CE can be recorded up to a height of 30.5 m a.s.l. A modern colluvial deposit of 1 m in thickness indicates an acute endangerment of the archaeological site by modern agriculture.

Kurzfassung: Flächenhafte Bodenerosion, ausgelöst durch intensive landwirtschaftliche Nutzung, führte ab Mitte des 14. Jahrhunderts u.Z. zur Zerstörung von Landschaftsstrukturen und in Mitteleuropa. Kolluvien, welche durch diese Prozesse entstanden und am Unterhang akkumulierten, wurden auf dem Fundplatz Gortz (westliches Brandenburg, Deutschland) durch die Hochschule für Technik und Wirtschaft Berlin im Jahr 2016 untersucht.

Konsequente Einzelfundeinmessung ermöglichte die Projizierung aller Funde auf eines der längs zum Hang verlaufenden Profile. Koordinatentransformation der Funde von der Profilansicht in die Draufsicht, ermöglichte die Visualisierung in einem GIS. Die Zusammenfassung benachbarter Schichten auf Basis der bodenkundlich-sedimentologischen Ansprache ermöglichte eine verbesserte Datierung der Kolluvien. Zusätzlich ermöglichte diese Methode die Datierung historischer Pegelstände der Beetzseekette, eines Teils des Flusssystems der Havel.

Im Ergebnis ließen sich für die spätslawische Zeit starke anthropogene Aktivitäten wie Mergelabbau und eine Uferbegradigung nachweisen. Über einen Verzahnungshorizont limnischer und kolluvialer Sedimente. ließ sich ein Pegelanstieg des Oberen Beetzsees von einem Wert unterhalb von 29.4 m Normalhöhennull (NHN) im 11./12. Jahrhundert u.Z. auf etwa 29.8 m NHN im 13. Jahrhundert u.Z. feststellen. Es lassen sich für das 13. Jahrhundert u.Z. jedoch auch vereinzelte Überschwemmungsereignisse bis in eine Höhe von 30.5 m NHN fassen.

Ein modernes Kolluvium von einem Meter Mächtigkeit zeigt die akute Gefährdung des Bodendenkmals durch die moderne Landwirtschaft.

1 Introduction and objectives

The combination of archaeological and soil-sedimentological investigations into erosion processes at archaeological sites enables reliable conclusions to be made about historical settlement phases and their paleo-environmental context. At the same time, erosion can be used to draw conclusions about the sub-recent to recent destruction of archaeological sites. In the best case, this can be used to derive scientific recommendations for the agricultural use of the land.

The Gortz 1 site, which is the focus of this study, has been subject to intensive agricultural use since the middle of the 20th century and is therefore subject to extensive soil erosion. Systematic field walking on sections of the site resulted in the collection of 7600 surface finds from 2.6 ha (Schenk, 2018). This accumulation can be seen as a clear indicator of the destruction of associated archaeological features. However, erosion processes are not just the result of modern agriculture alone; rather, they are associated with many anthropogenic interventions in existing landscape structures since the Neolithic Age. The consequence of soil erosion is a shift of the topsoil from the upper slopes to the lower slopes and the foot of the slope and beyond. These relocated soils are referred to as colluvia. Almost every anthropogenic activity phase leads to the formation of a colluvial deposit. It often contains material remains from when the deposit was first laid down. The colluvial deposit thus represents a sort of archive of the activity phase, which can be dated archaeologically via the associated ceramics. The thickness of the colluvia gives an indication of the intensity of the activity phase. If very little or no ceramics can be found for an epoch, this is an indication of an anthropogenic resting phase, i.e. a period in which no ceramics were used or relocated which could indicate less intensive human activity. The terms activity and resting phase are used according to the definition of Bork (Bork et al., 1998).

For the investigation presented here, the shore location of the archaeological site plays a significant role. The site is connected to the Havel river system via the Beetzsee chain of lakes. Therefore, dating of lacustrine deposits enables us to draw conclusions about the former spatial extension of water bodies in the wider landscape. These conclusions extend far beyond the boundaries of the site.

The aim of the study is to determine the former erosion history, paleo-environmental context and sub-recent to recent history of the destruction of this archaeological site. The research presented in this paper focuses on the following objectives:

1. dating of colluvial and lacustrine deposits,
2. categorization of phases of anthropogenic activity and resting,
3. investigation of historical water levels in the Beetzsee chain of lakes and the associated landscape development, and
4. assessment of the present-day risk to the archaeological site.

2 Research area

Located within the wider Havel river system, the archaeological site of Gortz 1 lies on the banks of a lake which is part of the Beetzsee chain of lakes. The lake chain was formed during the Brandenburg glacial stage (24–17 ka BP) in the Weichselian High Glacial, as a subglacial drainage channel (Lippstreu and Hermsdorf, 2010). The maximal extent and intermediate positions of the ice sheet were located south of or probably through this channel during this period (Stackebrandt and Lippstreu, 2010). The Beetzsee chain of lakes ex-

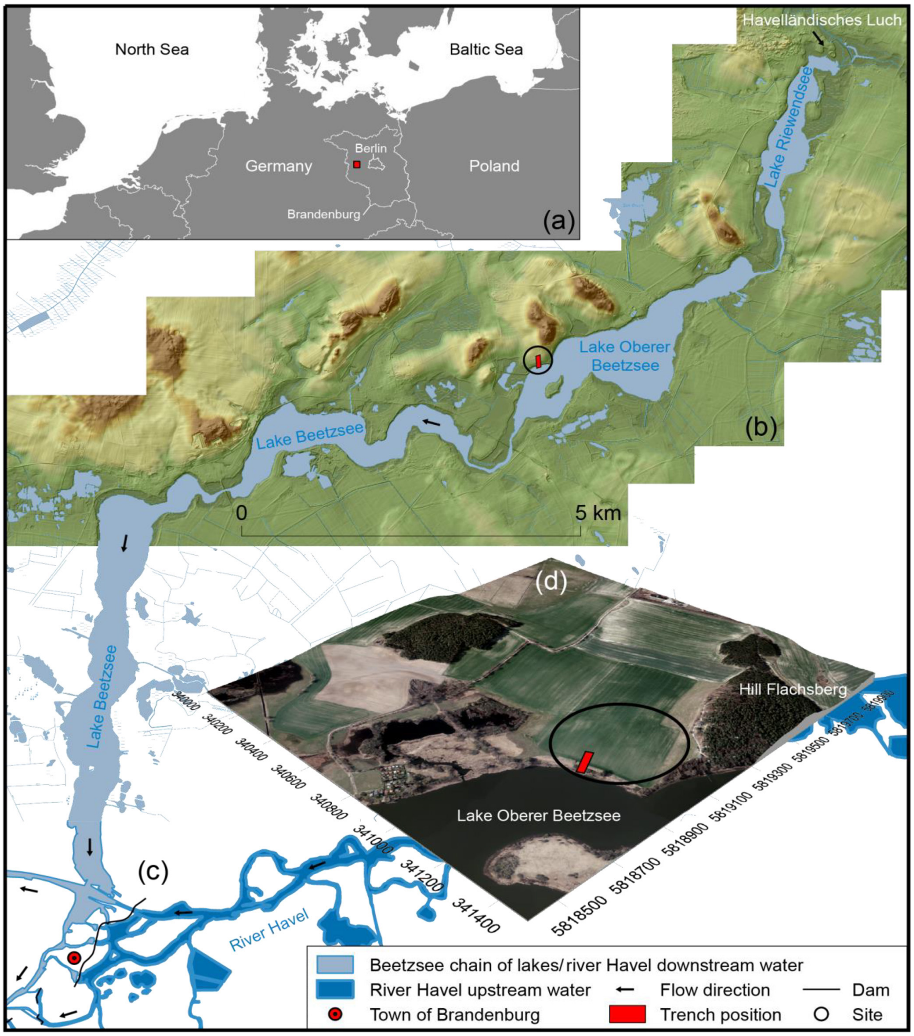

Figure 1. The Beetzsee chain of lakes in northeastern Germany **(a)** with a floodplain and moraine landscape encompassing it **(b)**. The lakes drain into the river Havel at the town of Brandenburg **(c)**. Within the town, the river Havel is divided into an upper and lower water level due to a mill dam system. They are referred to as the upstream and downstream water **(c)**. The position of the trench at the shore of the lake Oberer Beetzsee in a slightly elevated terrain model with view to the northwest is shown in panel **(d)**.

tends over more than 30 km from the wetland area Havelländisches Luch in the north to the town of Brandenburg in the south, where it drains into the river Havel (Fig. 1b, c). The chain is thus part of the lowland and floodplain landscape of the river Havel. On the northern and northwestern banks, the lowlands merge into an undulating, partly hilly, moraine landscape (Lippstreu, 2010). Within this transitional area, the site of Gortz extends from the southwest slope of the Flachsberg hill to the shore of the lake Oberer Beetzsee (Fig. 1d). In the riparian zone, colluvial deposits resulting from different settlement phases are interwoven with lacustrine deposits, both of which lie above boulder clay and gravelly sands. The most common soils around the lake chain are Brunic Arenosols, which also occur as Brunic, Endogleyic Arenosols or Cutanic Luvisols (Abrubtic, Arenic). In the riparian zone, the geological subsoil is mostly formed by Hemic Histosols (Eutric, Drainic) and Mollic Gleysols (Arenic) (LBGR, 2018).

Archaeological evidence of anthropogenic activities in the region can be found from the Mesolithic Period (9600–5300 BCE) onwards and for the entire Holocene (BLDAM, 2019). Based on the available sources of information, the study focuses primarily on the period of the last 1000 years. A particular focus is on the period from the late 11th century to the early 13th century CE. In this period the areas east of the river Elbe were strongly influenced by the colonization of land, which was organized by German regional rulers and supported by the Christian clergy. During this process, from the mid-12th century CE, German settlers were brought into the area, which had previously been inhabited by Slavic people. For the Slavs this meant the end of their political independence (Brather, 2001).

In archaeological features, the colonization of the Slavic region is highlighted by a slow transition to a new type of ceramic (Brather, 2001). Belt decorations are typical of ceramics from the Late Slavic Period. The Late Slavic Period roughly covers the 11th and 12th centuries CE for the area east of the river Elbe (Brather, 2001). From the middle of the 12th century the German settlement took place, which is also called the Early German Period. This was accompanied by a soft, blue-grey earthenware, which was already being replaced by the higher-quality hard grey earthenware as early as 1200 CE (Mangelsdorf, 1994b). The introduction of new technologies, such as the heavy plough, or the founding of new towns, led to far-reaching changes on the economic and infrastructural level (Brather, 2001). Large-scale agricultural cultivation, damming and hydro-melioration projects began to influence the water level of the middle and lower Havel, which led to lasting changes that are still visible in the landscape today (Kaiser et al., 2018). This raises the question of the extent to which the Gortz site was affected by these changes.

In Slavic times, the banks of the Beetzsee chain of lakes was one of the most densely settled areas in the Havelland area, with the large settlement chamber of Brandenburg in the south and Riewend in the northeast (Sasse, 1987). The Gortz site is situated half way up in an elevated position, from where there is a wide view over the lakes. Due to its surface finds, the site is referred to in the literature as a medieval deserted village, which must have existed at least from the Late Slavic to the Early German Period (Krenzlin, 1956; Mangelsdorf 1994a). Today there is an extensive field in this location. The village of Gortz, which still exists today, was founded about 2 km away in a higher location, although the tract of land on which the site sits has retained the name "Die alten Dörfer" (the old villages) (Krenzlin, 1956). These field names like "Dorfstelle", "Wüste Dorfstätte" and "altes Dorf" (village place, desert village site and old village) indicate that the original location was abandoned in the Late Slavic/Early German transition period (Krenzlin, 1956).

The archaeological investigations, carried out by Professor Thomas Schenk from the University of Applied Sciences Berlin since 2014, show a multi-period settlement history, which stretches from the Neolithic to the High Middle Ages. This is reflected in the numerous finds, some of which are unique in the Brandenburg region. The settlement character and the special significance of the site are reflected in the numerous metal finds covering a broad spectrum, as well as a large number of recognizable pits and hearths (Schenk, 2018).

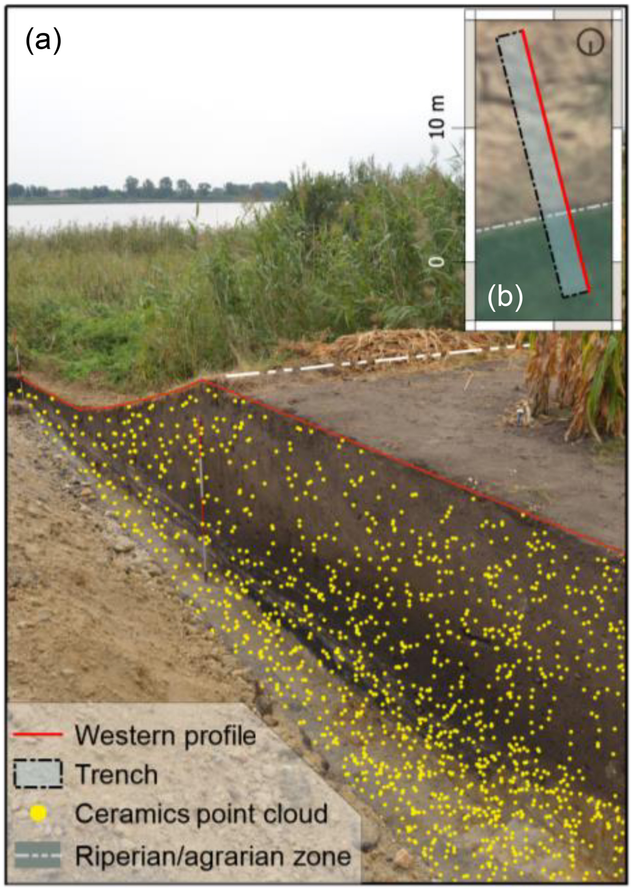

Figure 2. Photo of the investigated trench which extends from the foot of the slope into the riparian zone of Oberer Beetzsee with view to the south. The point cloud represents the ceramics recorded tachymetrically during the excavation, which was later projected onto the western profile of the trench during the post-excavation evaluation **(a)**. The position of the western profile in the plan view (plan was oriented to the south), which served as the visualization layer for the point cloud, is shown in panel **(b)**.

3 Methods

Since 2014 the University of Applied Sciences Berlin has been researching the landscape archaeology of the region around the Beetzsee chain of lakes. This includes geophysical prospection, field-walking surveys, sieving, and counting material from test pits and excavations. The Gortz site has been a special focus, due to its diachronic settlement history, its location and the acute threat posed by its agricultural use. In order to investigate the colluvial deposits which have accumulated on the foot of the slope, a 20 m long trench was cut following the direction of the slope, from the foot of the slope down to the riparian zone of the lake Beetzsee (Figs. 1d, 2). The trench was dug down to the C horizon. This resulted in two longitudinal profiles following the direction of the slope with a length of 20 m and a depth of over 2 m. The longitudinal profiles show the stratigraphy of the colluvial deposits. Only the western profile was used for the post-excavation evaluation (Fig. 2a, b).

In order to date the colluvial deposits, not only the finds from the profile wall but all finds from the trench should be

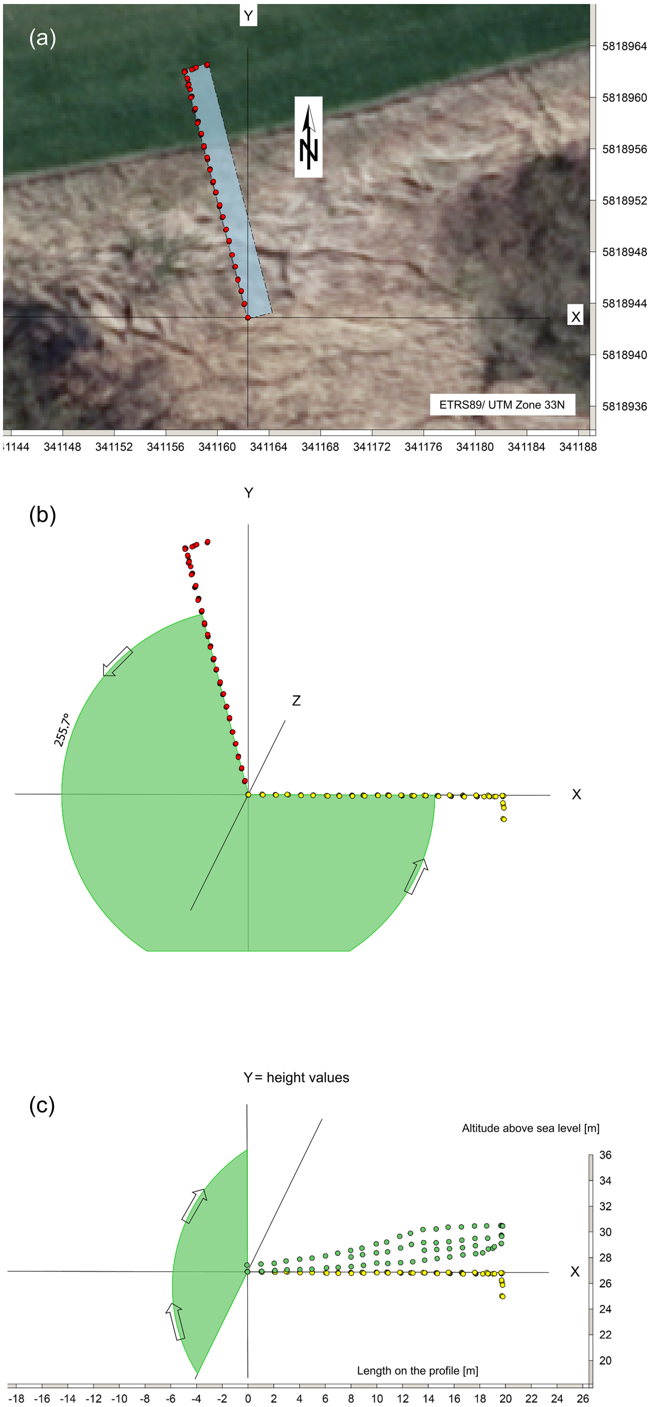

Figure 3. Rotation of the point cloud by matrix multiplication using the photogrammetry points of the western longitudinal profile as an example.

used[1]. For this reason, the position of every find was recorded using a total station (Fig. 2a). During the post-excavation evaluation, all identifiable ceramic fragments were archaeologically dated.

The visualization of the western longitudinal profile and the subsequent dating of the layers was achieved using QGIS 2.18.3. In order to enable the visualization in a GIS, the first step was to project the tachymetrically recorded point cloud of all finds of the trench onto the profile wall (Fig. 2a). In a second step, the profile was tilted from the profile view to plan view. A matrix multiplication in Excel served as an aid for this process, in which points with xyz coordinates can be rotated around the three spatial axes (X, Y, Z) at will (Kühnlein, 2019). This manipulation of the coordinates becomes necessary if the profile is not aligned with one of the cardinal axes (north–south $= Y$, west–east $= X$) shown in Fig. 3a. Prerequisites are that

A: the angle of deviation from one of the cardinal axes is known and

B: the complete dataset of a trench is summarized in one Excel table.

For the projection onto the profile, the point cloud was rotated around the Z axis until it had an east–west orientation. The points thus receive a new artificial easting, which lies exactly on the X axis (Fig. 3b). Without this step, the finds could only be displayed distorted in GIS. In a second step, the tilting into the plan view took place by defining the height values as the new northing (Fig. 3c). The easting coordinates are then reset to an artificial zero point so that profile metres (metres on the profile) can be displayed on the X axis (Fig. 3c). In order to generate a visualization layer, the western profile following the direction of the slope was recorded photogrammetrically and the photos were georeferenced in QGIS. This method of rotating coordinates allows an unlimited number of profiles with their real height values to be displayed side by side and compared within one project file. The layers were then redrawn and dated based on the ceramic. Many of the thin layers proved particularly difficult to reliably date. Where finds were measured further away from the profile wall, they could be considered as belonging to any number of adjacent layers. Therefore, the 58 recorded strata were combined, using a pedological and sedimentological approach, into five phases of anthropogenic activity (Fig. 4).

4 Results and discussions

The elevation heights refer to the German Main Elevation Network (DHHN92) and are given here as metres above sea level (a.s.l.). The easting coordinates are given here as metres on the profile (o.t.p.). Of the approximately 1600 diagnostic fragments, about half could be dated (Reichel and

[1] The background is that finds within colluvial deposits have often been displaced and therefore have less significance regarding the exact timing and circumstances (archaeological features) of their deposition. However, with a greater number of finds, even if they are potentially predominantly relocated, a more reliable dating of a layer can be made.

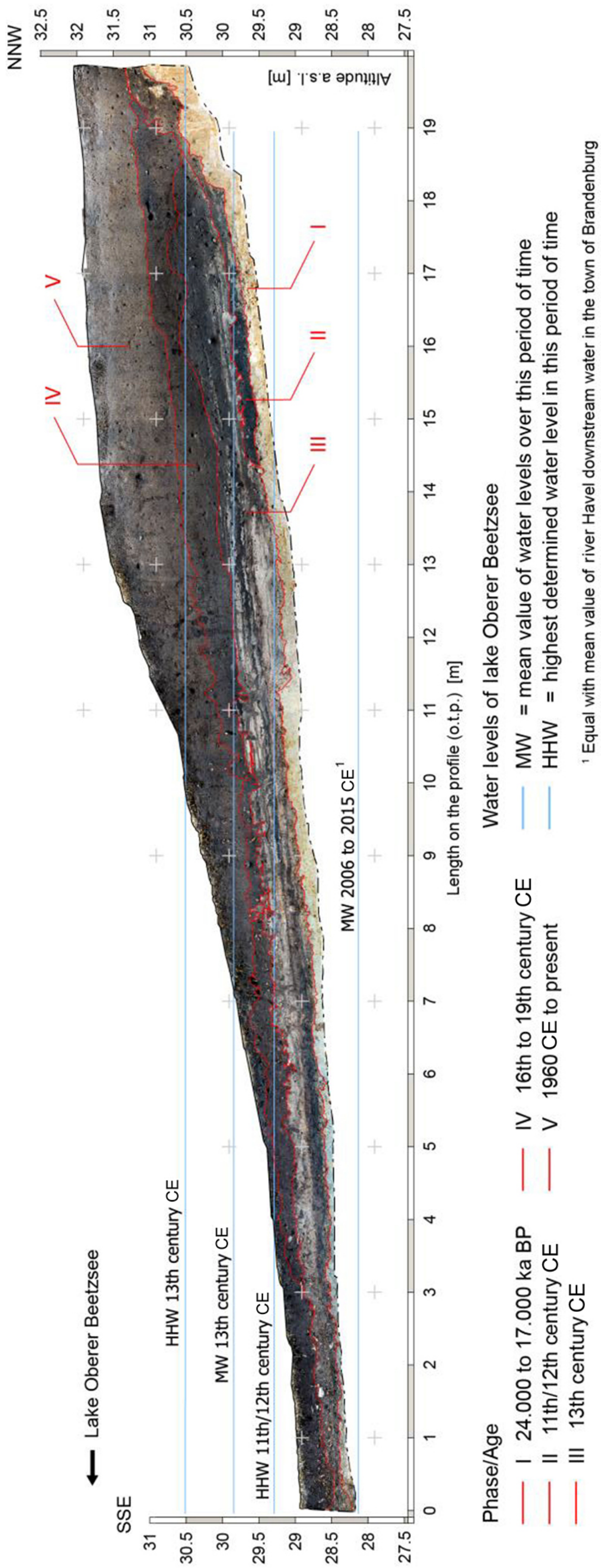

Figure 4. Photogrammetry of the western profile following the direction of the slope. The trench extends into the riparian zone of Oberer Beetzsee. The five phases were combined, using a pedological–sedimentological approach, and dated via the diagnostic ceramics of the entire trench. The dating allowed historical water levels to be determined for the periods of the 11th/12th and 13th centuries.

Schenk, 2019). This archaeological identification of ceramic fragments formed the basis for the dating of the different phases. In cases where bioturbation could be ruled out, the most recent ceramics give the terminus post quem for the deposition of a layer (Bork et al., 1998). Phase I contains no ceramics and corresponds to the C horizon consisting of boulder clay and gravelly sands. Between 11.5 and 18 m o.t.p., the sequence of layers is strikingly even and straight. Gravelly sands dominate here. From 18 to 20 m o.t.p., the sequence of layers is reminiscent of a staircase that, in several steps, changes the height level by more than 1 m. This part of phase 1 consists of boulder clay. The transition to phase II, which lies above, is sharply defined. Characteristic features of soil formation are missing. The straight, even upper edge of the C horizon can be interpreted as a result of ground levelling and the steps as remains of clay quarrying. The latter in particular demonstrates an anthropogenic intervention here (Fig. 4).

Phase II can be dated to the 11th/12th century CE on the basis of 42 % of all ceramic sherds from this phase being Late Slavic (Reichel and Schenk, 2019). Two fragments from the German Middle Ages and a sherd from the Early Modern Period (1500–1700 CE) (Verband der Landesarchäologen, 2014) were probably introduced to these layers by strong bioturbation. The only stratum from the entire profile that can be interpreted as an in situ culture layer, due to the presence of lenses of ash and a high proportion of charcoal pieces, lies directly on the straightened C horizon between 14 and 17 m o.t.p. (Fig. 4). The absence of colluvial deposits, which are older than Slavic ones, is conspicuous, since much older settlement phases are documented on the site, in particular from the Early Bronze Age (2100–1500 BCE), the Roman Period (9 BCE–375 CE) and the Migration Period (375–565 CE) (Verband der Landesarchäologen, 2014). All older colluvial deposits were obviously removed in the course of clay quarrying. Therefore, the in situ layer can be used for dating the clay quarrying and ground levelling into the Late Slavic Period.

On the side that borders the lake, the culture layer is cut possibly by wave erosion. There are several thin layers of light lacustrine sand running up to this stratum and covering it. Furthermore, a series of holes filled with lacustrine sands can be seen impressed into the culture layer. These holes can be interpreted as cattle hoof prints and delineate the shoreline during the Late Slavic Period in this area. At 11 m o.t.p., the straightened C horizon is interrupted by a 0.2 m high sill (Fig. 4). Here the blue-grey earthenware of the German Middle Ages appears in large numbers. The sill obviously marks the edge of the riparian zone that had been levelled. In the 11th/12th century CE, the lake level must have been below this sill, suggesting a height of 29.4 m a.s.l. ±0.2 m. Otherwise, no culture layer interspersed with ash lenses could have formed and been preserved between 14 and 17 m o.t.p. (Fig. 4).

Phase III is dominated by Slavic ceramics with 35 % of all ceramic sherds from this phase. Blue-grey earthenware is represented by 7 % of all ceramic sherds from this phase and allows the phase to be dated to the 13th century CE (Reichel and Schenk, 2019). The colluvial deposits in phase III between 16 and 19 m o.t.p. can be interpreted as Slavic. Strong indicators are the high humus content when compared to the other colluvial deposits of the profile and the charcoal particles, which cause a darker-coloured sediment (Schatz, 2011).

The hydrochloric acid test (10 % HCl) showed a carbonate content of > 10 %. Thus, the colluvium is rich in carbonates (Ad-hoc-AG Boden, 2005). A high calcium carbonate content also indicates significant, if partial, erosion on the upper slope. This suggests intensive settlement activity in this phase. Due to finds of the commonly associated grey earthenware and Pingsdorfer Ware in other trenches of the site, it is likely that the German settlement started in the late 12th or early 13th century CE. So far no finds can be classified as dating back to the 14th and 15th centuries CE, probably because the village had already been relocated during the 13th century CE. However, the colluvial deposits indicate that the German settlement probably existed for less than a hundred years.

The reason for the abandonment of the settlement of Gortz remains unknown. However, erosion processes could have played a role, which is indicated by the partially high carbonate content in phase III. Between 1150 and 1250 CE, the colonization of the Havelland area led to an extensive settlement and restructuring of the landscape, the like of which had never been seen before. In the sequel, many newly founded settlements in the Havelland area were abandoned from the turn of the 12th to 13th centuries CE. Taking into account the fact that the settlers did not know the terrain and the soils, it is likely that in many cases they became victims of erosion processes they caused and had to give up the site (Mangelsdorf, 1994a).

In phase III, on the side that borders the lake, between 8 and 17 m o.t.p., there is a horizon of interlocking dark colluvial deposits and lighter-coloured lacustrine sediments (Figs. 4 and 5). Incorporation of swirled dark humus material within the entire interlocking horizon indicates that sedimentation took place in an area of slightly moving standing water. Thus, the interlocking horizon can be interpreted as a riparian zone. Each of the thin, light-coloured layers was formed during a flooding event, whereby the deposition may have occurred at short intervals. Straight above the aforementioned sill (Fig. 4, 11 m o.t.p) blue-grey earthenware of the German Middle Ages appears in large numbers. Thus, the interlocking horizon can be clearly dated to the 13th century CE and is therefore part of phase III. The flood events indicate rising water levels during this period. The interlocking horizon reaches up to a height of at least 29.8 m a.s.l. (Fig. 4). Evidently, in the 13th century CE, the level of Oberer Beetzsee rose to this height. However, isolated flooding events

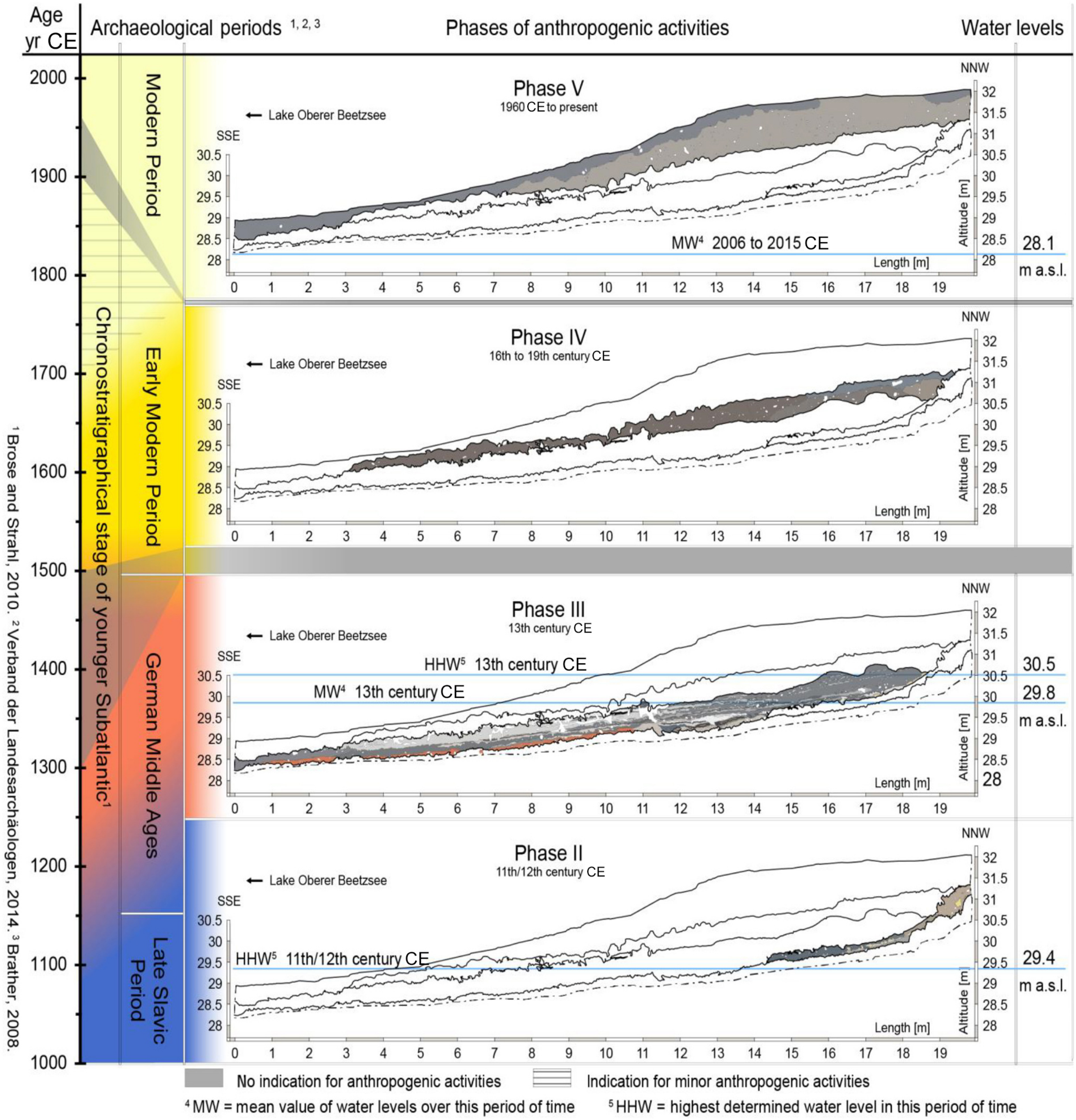

Figure 5. Development of the anthropogenic activities at the site Gortz from the Late Slavic Period to the present day, and the associated development of water level changes of the lake Beetzsee.

during the 13th century CE can be recorded up to a height of 30.5 m a.s.l. (Fig. 4).

This increase has regional significance, as the Beetzsee chain of lakes is connected to the lower Havel river (Fig. 1). Historical sources indicate that water levels in the river Havel region rose by an average of 1–2 m due to medieval mill dams (Driescher, 2003). The Beetzsee chain of lakes drains into the river Havel at the town of Brandenburg. Since the first half of the 13th century CE the river Havel has been divided into an upper and lower water level by a mill dam system (Müller, 2009). They are referred to in this study as the upstream and downstream water. The most recent study assumes that the dam system caused a water level rise of 1.5 m in the upstream water (Kaiser et al., 2018). However, the Beetzsee chain of lakes drains into the river Havel downstream from the dam system (Fig. 1) The dams associated with medieval mills may not have played a direct role in the rise of Beetzsee, whereas fish weirs could be responsible for rising water levels (Kaiser et al., 2012). Nowadays the downstream water level values in the town of Brandenburg are also valid for the Beetzsee chain of lakes. Between 2006 and 2015, the mean value of the downstream water level was at 28.13 m a.s.l. (WSA Brandenburg, 2015). Thus the water level of Oberer Beetzsee in the 13th century CE was 1.6 m above the present-day level.

Phase IV features the highest number of archaeological finds in the whole trench (Reichel and Schenk, 2019). Yellow-glazed and occasionally also brick-red earthenware date the colluvia to the 16th/17th century CE at the earliest. This was a time when the settlement had already been abandoned for about 300 years and the site was being used agriculturally. A later origin of phase IV is also conceivable, provided that in the 18th/19th century CE only little domestic waste had reached the fields (Fig. 5). The transition between the foot of the slope and the shore area was until this period less steep than today (Schenk, 2018).

Phase V contains a balanced spectrum of ceramics from Bronze Age to current times. Thus this is the only phase with recent ceramics (Reichel and Schenk, 2019). In addition, associated finds, such as plastic bands and the light colour of the substrate, typical of recent deposits, also suggest a Modern Period colluvia (Fig. 5). Its deposition can be associated with agro-structural measures that had a strong influence on landscape development from the 1960s to the 1980s. Land consolidation and collectivization led to destructions of important soil-protecting landscape structures (Bork et al., 1998). These measures have probably also been implemented in Gortz by the local agricultural producer cooperative. Within > 70 years a colluvial deposit of 1 m thickness has formed. This impressively demonstrates the endangerment of the archaeological site by modern agriculture.

5 Conclusions

Consistent tachymetric mapping of the finds of a trench and their projection onto one of the longitudinal profiles within a GIS environment, in combination with a sedimentological–pedological approach to combine neighbouring layers into phases, led to new insights into the settlement and landscape development of the studied site and its surroundings. The advantages of our approach are an unambiguous spatial allocation of the finds. In addition, not only the ceramic embedded in the profile wall but also the datable ceramic from the entire trench can be used to date the phases. The larger number of ceramic fragments that can be used for dating can provide a more reliable determination of the age of the phases.

On the basis of the recovered ceramics, it was feasible to approximate the sedimentation time of the differing colluvial phases. The timing of the sedimentation of the shoreline deposits in the interlocking horizon could thus be dated indirectly.

From the Late Slavic Period onwards, phases with settlement processes as well as phases with anthropogenic resting can be observed at the site. Especially in the Late Slavic settlement phase, it can be proved that intensive activities in the shore area such as the straightening of the bank and clay quarrying took place. Cattle hoof prints show the course of the riparian zone at that time. The interlocking horizon indicates a change in the shoreline from the 11th/12th to 13th centuries CE. During this time, the lake water level rose from < 29.4 m a.s.l. to approximately 29.8 m a.s.l. Thus the water level of Oberer Beetzsee in the 13th century CE was 1.6 m above the present-day level.

Up to now no colluvial deposits could be assigned to the 14th and 15th centuries CE, so that a resting phase on the site can be assumed (Fig. 5). This is probably because the settlement had already been deserted in the 13th century CE.

The modern colluvial deposit of 1 m thickness indicates an acute endangerment of the archaeological site. The cultivation of maize, which has been practised here for years, is also responsible for the high erosion rates. But also the cultivation of asparagus, which is widespread in the region, would entail far-reaching soil interventions, which would lead to the irreparable destruction of archaeological features in a short time. It is clear that a continuation of agricultural use in its present form will inevitably mean the loss of remaining archaeological features in the coming decades.

Data availability. The data presented here are available online at https://opus4.kobv.de/opus4-htw/frontdoor/index/index/docId/363 (last access: 7 July 2019) (Reichel and Schenk, 2019).

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Express report

Archaeological prospections in the Roman vicus Belginum (Rhineland-Palatinate, Germany)

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Abstract: The Roman vicus Belginum and the associated Celtic–Roman cemetery have been the subject of systematic archaeological research since 1954. Since 2004, archaeological prospections have been carried out in and around Belginum. Participants included students from the universities of Leipzig, Trier, and Munich as part of study-accompanying field work.

This paper deals with the prospections of 2004 and 2016, when nearly 2 ha of land south of the federal road B327 (Hunsrückhöhenstraße) were surveyed. The study area is located on a NW-to-SE-running hillside. All non-local objects present on the surface were collected and three-dimensionally recorded. Previously in 2013, the area was geomagnetically prospected by Posselt & Zickgraf (Marburg). Both surveys revealed a hitherto unknown extent of the vicus about 200 m to the southwest. The findings date back to the late first to third centuries common era.

All finds (ceramic, bricks, roof slate, glass, and metal) were recorded and analysed in a QGIS and ArcGIS environment together with lidar scans, the geomagnetic data, and other geographical information. The overall distributions of bricks and pottery were studied in detail. The distribution of bricks is in particular connected to the individual plots, while the pottery is mainly concentrated in the backyards. Regarding surveys in other Roman vici, the brick distribution could be a helpful indicator to identify plots, when no geophysical information is available.

Kurzfassung: Der römische *vicus Belginum* und das zugehörige keltisch-römische Gräberfeld sind seit 1954 Gegenstand systematischer archäologischer Forschungen. Seit 2004 werden archäologische Prospektionen in und um Belginum durchgeführt. Beteiligt waren Studierende der Universitäten Leipzig, Trier und München im Rahmen von Lehrveranstaltungen.

Diese Veröffentlichung stellt die Ergebnisse der Prospektionen von 2004 und 2016 vor. Prospektiert wurden etwa 2 ha Fläche südlich der Hunsrückhöhenstraße B327. Das begangene Areal liegt auf einem von NW zu SO verlaufenden Hang. Sämtliche auf der Geländeoberfläche beobachteten nicht-lokalen Gegenstände wurden dreidimensional eingemessen und eingesammelt. Bereits 2013 war das Gebiet von der Firma Posselt & Zickgraf (Marburg) geomagnetisch prospektiert worden. Beide Surveys ergaben eine bis dahin unbekannte Ausdehnung des Vicus um 200 m nach Westen. Die datierbaren Funde, überwiegend Keramik, gehören in den Zeitraum zwischen dem späten 1. Jh. und dem 3. Jh. n. Chr.

Sämtliche Funde (Keramik, Ziegel, Dachschiefer, Glas und Metall) wurden in einer Lehrveranstaltung aufgenommen. Die Daten wurden in einer QGIS- und ArcGIS-Umgebung zusammen mit Lidar-Scans, den geomagnetischen Daten und anderen geographischen Informationen analysiert. Die Gesamtverteilungen der Ziegel und Keramik wurden detailliert untersucht. Vor allem die Verteilung der Ziegelfunde folgt den einzelnen, auf dem Magnetometerplot erkennbaren Parzellen. Die Keramik ist dagegen überwiegend im Hinterhofbereich konzentriert. Bei zukünftigen Prospektionen in anderen römischen *vici* kann die Verteilung der Ziegelfunde ein wichtiges Hilfsmittel zur Identifizierung von Grundstücksparzellen darstellen, wenn keine geophysikalischen Daten vorliegen.

1 Introduction

Wederath-Belginum (Gde. Morbach, Kr. Bernkastel-Wittlich; localization: Fig. 1, insert) is one of the remarkable rural archaeological sites in Rhineland-Palatinate, Germany. The archaeological ensemble consists of a Celtic and Roman cemetery, the Roman vicus Belginum with at least three sanctuaries and an early Roman military camp (Fig. 1). The ancient name of the vicus is known from a Roman inscription (... *vicani belginates*...) and from the well-known *Tabula Peutingeriana* (Haffner, 1989, inside back cover).

Belginum was located at the intersection of the ancient west–east road, linking the capitals of the Roman provinces Gallia Belgica and Germania Superior, Trier-Augusta Treverorum and Mainz-Mogontiacum, and the north–south route connecting the rivers Moselle and Nahe (Haffner, 1989).

The site Wederath-Belginum has been the subject of systematic archaeological research since 1954 (overview in Haffner, 1989, and Cordie, 2007). The burial ground has been comprehensively published in six volumes so far (details and references in Cordie, 2007).

Excavations in the settlement area itself were carried out in 1969–1973 and 2000–2014. The excavations showed that strip houses were present at the Belginum. They are typical for the Roman northwest provinces. The plots are about 10 m wide and up to 80 m long. A (stone) cellar is located near to the street and the building begins above the cellar. A porticus is set in front of the house. The house with half-timbered construction extends about 20–25 m into the rear part of the property (Cordie et al., 2013). Such a plot organization can also be seen on the images of the new geomagnetic prospections (see Figs. 2–3).

2 Material and methods

2.1 Prospection and data

Since 2004, prospections of various types have been carried out at the Belginum site in the framework of course-related university training with the aim to gain knowledge of the Iron Age settlement (Lukas et al., 2012), the Roman land use, and the extent of the vicus. Students participating came from the universities of Leipzig (UL), Trier (UT), and Munich (LMU). Within Belginum's surroundings (Fig. 1), several *villae rusticae* and at least one settlement of pre-Roman Iron Age could be identified as reported by Teegen et al. (2014, with further references).

2.1.1 Prospection 2004

Already in late autumn of 2004, an approximately 50 m wide and 200 m long strip of ground had been prospected by UL students and staff, along the road to Hintzerath (EV2004,167) (Fig. 1 No. 1). A large number of finds were discovered in 1670 spots. The Roman pottery and the glass finds generally date back to the first to third centuries common era. The find distributions were analysed in a LMU bachelor thesis by Mägdefessel (2018) using the geographic information system QGIS (QGIS Development Team, 2018).

2.1.2 Geomagnetic prospection 2013

In advance of the construction work for the federal road B50neu, large areas south of the federal road B327 (Hunsrückhöhenstraße) were geomagnetically prospected in 2013 by the company Posselt & Zickgraf (Marburg) (see below Figs. 2–3). Surprisingly, it turned out that the vicus extends about 200 m further to the west.

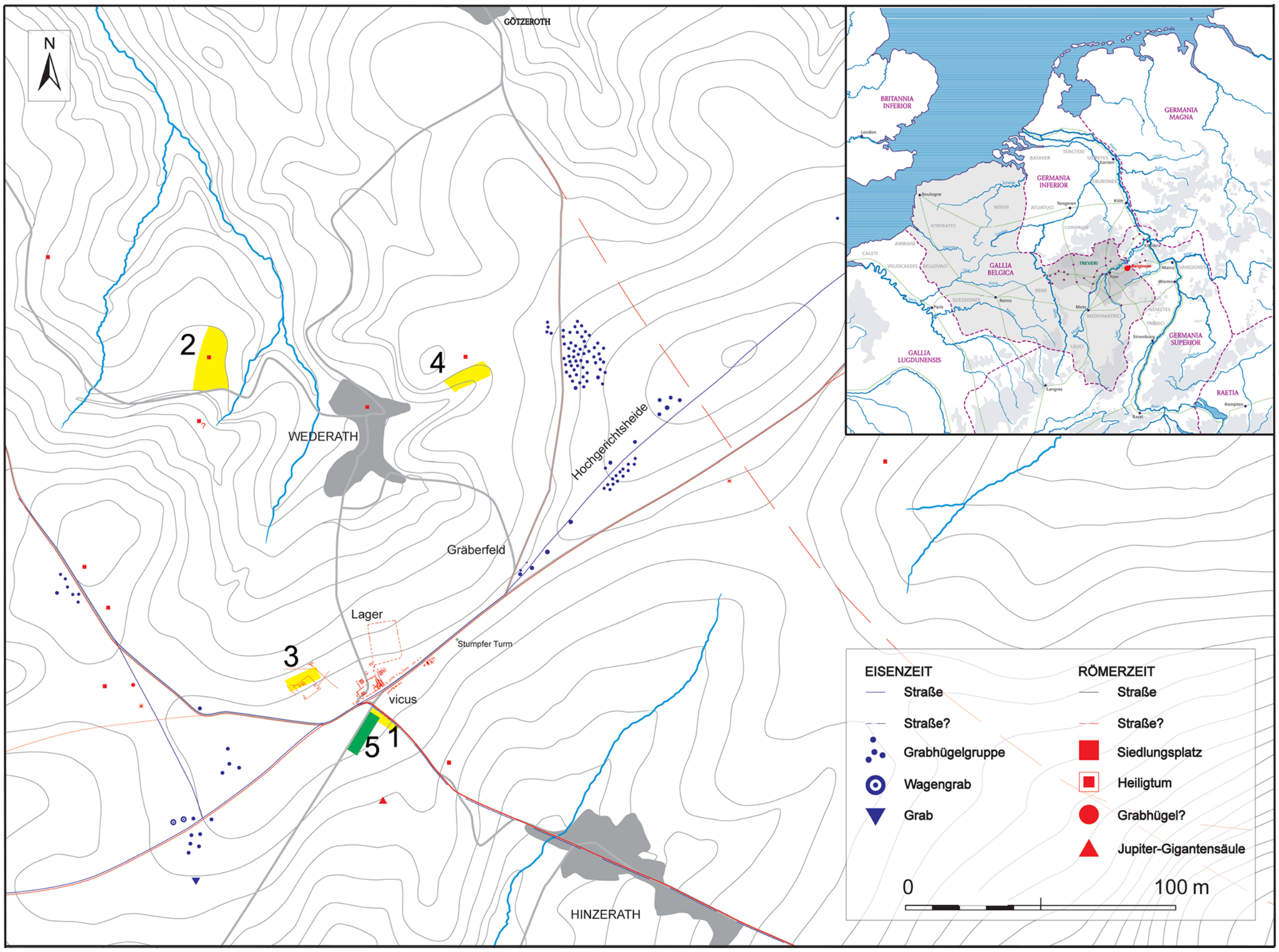

Figure 1. The archaeological site Wederath-Belginum during the Iron Age (Eisenzeit) and the Roman times (Römerzeit). Localization of archaeological features, and the survey areas from 2004 to 2008 (1–4, yellow) and 2016 (5, green). Archaeological features are as follows. Vicus: Roman vicus; Lager: Roman military camp; Gräberfeld: Celtic and Roman cemetery; "StumpferTurm": medieval tower. Legend is as follows. Straße: road; Grabhügelgruppe: group of tumuli; Wagengrab: wagon burial; Grab: burial; Siedlungsstelle: *villa rustica*; Heiligtum: sanctuary; Jupiter-Gigantensäule: column of Jupiter and the Giants (map: Marco Schrickel, Jan König, Wolf-Rüdiger Teegen). The insert shows a localization of the site Belginum (red) in the Roman province Gallia Belgica (map: Archaeological Park Belginum).

2.1.3 Prospection 2016

In October 2016, a joint field exercise for 10–15 students of (geo-)archaeology and geo-informatics organized by UT and LMU was carried out in the vicinity of Belginum in an agricultural field of approximately 1 ha in size located at the southern side of the federal road B327 within the parish Hundheim (Fig. 1 No. 5) (EV2016,205).

During the first couple of days, the students surveyed the field on a 1 m density grid. All non-local finds (pottery, bricks, glass, metal, etc.) were deposited into plastic bags together with a unique identification code. These were then three-dimensionally sited by means of a total station (Leica) and a differential Global Navigation Satellite System (GNSS) (TopconPositioning Systems, Inc.). As collected fragments in 2016 were abundant, the finds of the site's western part were sampled at 5 m × 5 m quadrants. All together 2856 find locations were sampled containing a total of 9979 finds.

The aim of this prospection was to gather information about dating and material culture in this newly discovered western part of the settlement.

2.2 Data integration and analysis in GIS

The archaeological finds were inventoried and classified into the general material groups pottery, bricks, roof slate, glass, and metal during another course at LMU. They were later recorded in an Excel spread sheet. In the consecutive GIS exercise in 2017, these tables were integrated into an ArcGIS geodatabase, which required reorganization of the standard archaeological table structure into an appropriate geodata format. The prospection areas of 2004 and 2016 partly overlap at the north-northeastern region south of the federal

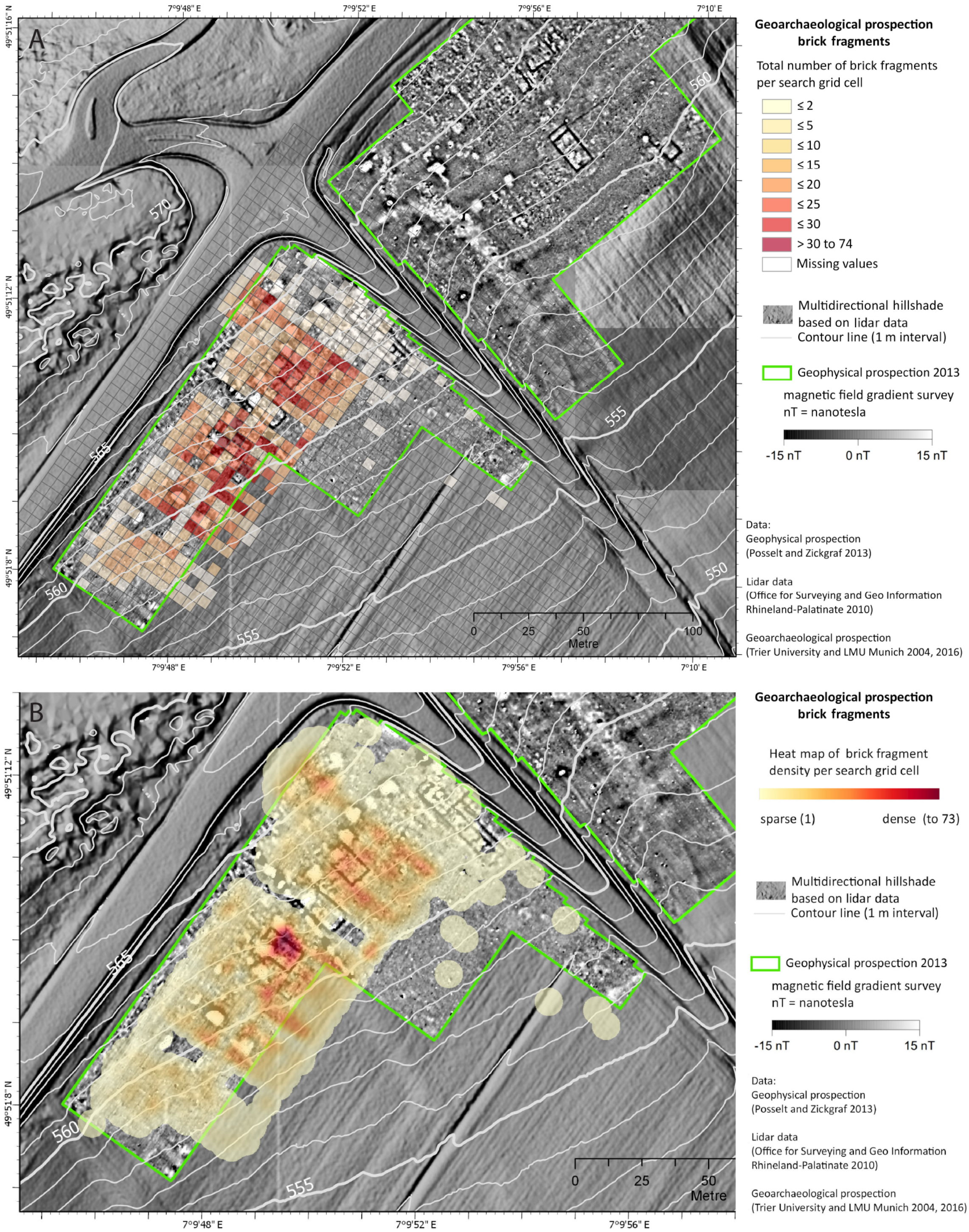

Figure 2. Wederath-Belginum, archaeological survey 2004, 2016. **(a)** Total number of brick fragments (1 to 74) per search grid cell (5 m × 5 m) in the western part of the vicus (GIS map: Johannes Stoffels). **(b)** Close-up of the heat map of brick fragments (1 to 74) per search grid cell (5 m × 5 m) in the western part of the vicus (GIS map: Johannes Stoffels).

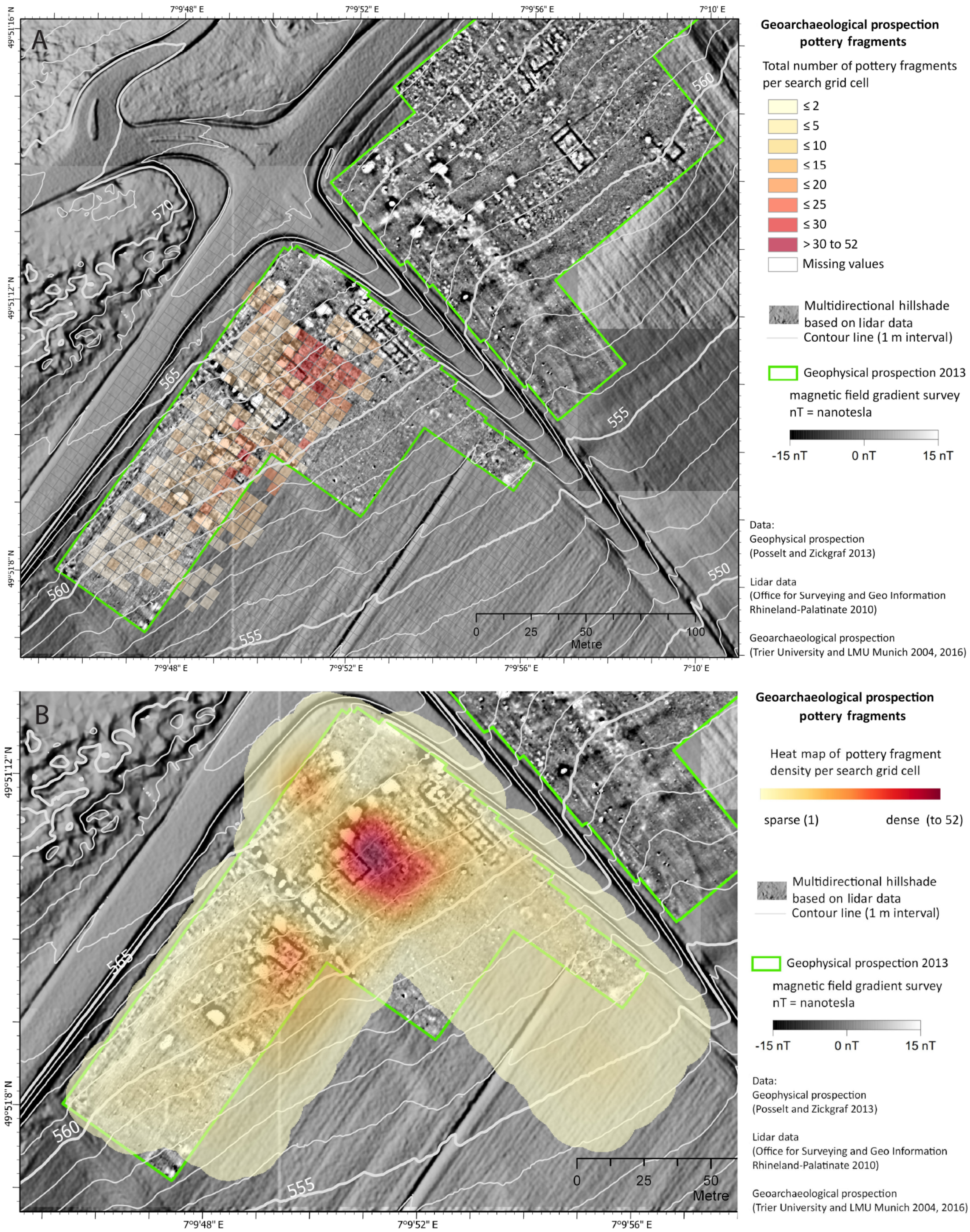

Figure 3. Wederath-Belginum, archaeological survey 2004, 2016. **(a)** Total number of pottery fragments (1 to 52) per search grid cell (5 m × 5 m) in the western part of the vicus (GIS map: Johannes Stoffels). **(b)** Close-up of the heat map of pottery fragments (1 to 52) per search grid cell (5 m × 5 m) in the western part of the vicus (GIS map: Johannes Stoffels).

road Hunsrückhöhenstraße B327 (see Fig. 1 No. 1 and 5). The 3-D position data were projected to ETRS89/UTM32N and archaeological attribute data were merged with the point data for further find density analysis following Allen (2016), exemplary for pottery and bricks. In concordance to the sampling, a regular fishnet of 5 m cells was generated and oriented to follow the study site orientation (SW–NE) as a base for density mapping by summarizing finds for each respective cell (Figs. 2a–3a). Finds were further described by kernel density maps (heat maps) visualizing the number of bricks or pottery fragments for a search grid cell of 5 m × 5 m (Figs. 2b–3b) (Silverman, 1986). Furthermore, the geomagnetic prospection, Rhineland-Palatinate's lidar scans, and topographic raster maps were available. From the lidar elevation data, a multidirectional hillshade raster and contour lines were derived at 5 m elevation intervals. The aim was (a) to explore the data and (b) to map and analyse the occurrence of material groups, which were also further analysed in a bachelor thesis at LMU (Over, 2018) using QGIS.

3 Results and interpretation

The classification and inventory of the finds during a course in winter 2016/17 at LMU revealed a dating in a time span from the late first to the third centuries common era. This is consistent with the results of the 2004 prospection (see above). During another course in winter 2018/19 at LMU, handmade pottery of the late Latène or early Roman period (second half of the first century before common era) was discovered. This is the first indication for a late Latène (late pre-Roman) to early Roman settlement at Belginum itself.

The data collected in the above-mentioned bachelor theses (Over, 2018; Mägdefessel, 2018) were summarized in the overall mapping using ArcGIS (see Figs. 2–3).

The geomagnetic prospection from 2013 (Posselt & Zickgraf) revealed several cellars and some houses south of the B327 (see Figs. 2–3). The width of the houses is mostly equal to the plot widths. There is, however, sometimes a small distance between the houses, as the excavations in the last decades have shown (Cordie, 2007). Every house has a quadrangular or rectangular cellar in its front part. The width of the cellars is sometimes equal to the house or plot widths. In general, the cellars are smaller.

The number of fragments per search grid cell and the kernel density map of the bricks (Figs. 2–3) show a clear relation to the single plots. The bricks are distributed from the cellars to the probable house extents up to the backyard area. This means a distance of 30 to 40 m. The finds concentrate in the longitudinal axis of the plots. There is a decreasing intensity of finds to the lateral periphery of the plots. The same distribution may be observed for the adjacent plots. We can, therefore, assume that the distribution of bricks mirrors the houses on the single plots. This is quite an important result for further archaeological prospections on Roman sites, where no geophysical information is available. Here, a reconstruction of the plots would be possible, using the density distributions of bricks.

Focussing on the density or heat maps of bricks within the houses (see Fig. 2), we can see a strong concentration of bricks within the houses. This is probably due to the fact that after leaving the houses at some point the roof truss collapsed inwards (see Bentz, 2013, p. 78). As a result, the roof tiles fell into the interior of the house. This is a quite different mechanism compared to earthquakes, where walls generally collapse to the outside (Stiros, 1995, p. 729, Fig. 4).

From the excavations of the years 1969–1973 and 2000–2014 in the vicus Belginum, we know that the place was not subject to a fire disaster, but had been abandoned. The descriptions of the ruins of the vicus in the early 19th century show that at that time some of the houses towered right up to the first floor (Merten in Cordie, 2007). In the middle and second half of the 19th century, stone and bricks were robbed for modern road and house construction and thus completed the destruction of the vicus. Today, not a single upright wall is present. However, part of the vicus must have already been demolished in late antiquity. The new *burgus*, discovered during rescue excavations in 2015, clearly shows the walls were constructed with secondary building materials.

The distribution of the ceramic sherds shows a different pattern (Fig. 3). Here, the finds are concentrated in the rear part of some houses and in the backyard area. The major concentration of pottery is present in the rear part and in the backyard of three houses in the northern part of the survey area (Fig. 3). From an archaeological perspective, this distribution makes sense. When a Roman strip house is excavated, the major quantity of (storing) vessels, glass, and other household items will be discovered in the backyard. Here, the waste pits are usually localized. The waste pits were partly destroyed due to agricultural work in the last 2 centuries, and their contents came to light. The plowing activity might shift ceramics and other finds downhill by about ≥ 5 m.

4 Prospect

This work has shown that curricular practical course prospections bring further insights into settlement archeology. This can be achieved with systematic field surveys, geophysical surveys, lidar scans, and aerial photographs obtained by plane, drone, or fixed-wing unmanned aerial vehicle.

The use of various archaeological and geophysical prospection methods and the following GIS analyses brought a significant gain in knowledge for the site Belginum regarding size and type of development – without excavation.

Data availability. For the next years, there is an ongoing project regarding the spatial distribution of pre-Roman and Roman findings in the vicus Belginum. This will result in some theses at LMU and UT. Furthermore, due to illegal activities of non-authorized detectorists, find co-ordinates will not be published. They will be, however, stored in due course in the find archive of the Rheinisches Landesmuseum Trier.

Author contributions. RC and WRT organized the archaeological prospection, funding, and the identification of the findings. RR and WRT were responsible for on-site data catchment. JS and RR organized the GIS course and GIS analysis. JS, RR, SM, and PO analysed GIS data. WRT and RC interpreted GIS data. WRT and RR wrote the paper with contributions from all co-authors.

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Express report

Archaeology and agriculture: conflicts and solutions

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1 Introduction

The archaeological soil archive that has been preserving information on human activities over thousands of years is extremely endangered by increasing land use and intensive agriculture in highly frequented regions.

Many archaeological cultural monuments are located in regions which have been settled since prehistory because of various positive location factors, such as fertile soils and sufficient water supply. In these areas modern agriculture produces high yields also today, and the arable land is therefore affected by intensive farming practices. This, in turn, puts the preservation of cultural heritage and soil archives at risk and could result in their irreversible destruction.

This paper reports common problems and approaches for problem-solving strategies that derive from daily practice and experience in cultural heritage management, as a contribution to further discussion in an international context.

The industrialization and intensification of agriculture since the 19th century has resulted in increasing losses of archaeological soil archives. Moreover, intensive soil cultivation leads to erosion in many regions, which has had a strong impact on soil conservation and on remaining archaeological structures. Land consolidation, removing boundaries of fields and terraces, has facilitated the use of large agricultural machines and enhanced erosion processes.

As a result, above-ground archaeological monuments such as tumuli fields, ramparts and ditches, which are better preserved in grassland or in the forest, will be completely flattened and disappear in agricultural landscapes (Fig. 1). Modern ploughs dig deeply into the ground and destroy any remaining structures. Large farming machines remove or shred stones and bricks including archaeological stone structures and walls. Ploughing also leads to the removal of soil and artefacts outside of the context of archaeological features and sites. Machinery use, fertilization and usage of chemical pesticides damage finds, which is particularly evident in heavily corroded metal objects. Also drainage of moorland for peat extraction and land reclamation is a substantial danger to the preservation of wetland sites with their wooden and organic objects that can be thousands of years old (Kretschmer, 2014).

2 Prospection and evaluation

One method to detect erosion as well as archaeological features is the evaluation of aerial photographs. Variances in height and vegetation colour can display archaeological features like ramparts, pits or burials. However, the clearer archaeological remains are visible in aerial photographs; the closer these remains are to the surface, the more vulnerable they are to total destruction (Fig. 2). A large number of archaeological remains picked up during field prospections indicate exposure and translocation of archaeological sites.

Soil mapping by soil coring is an appropriate method for the evaluation of archaeological site conditions. The devel-

Figure 1. The rampart of the Celtic oppidum Finsterlohr (Creglingen, Baden-Württemberg) was partially flattened by ploughing (Landesamt für Denkmalpflege im Regierungspräsidium Stuttgart, LAD, Baden-Württemberg/I. Kretschmer).

Figure 2. Aerial photograph of the remains of the Gothic church and abandoned medieval monastery in Remchingen-Wilferdingen (Baden-Württemberg) (LAD, Baden-Württemberg/O. Braasch).

opment of a soil profile helps to estimate the amounts of erosion and accumulation, especially in landscapes where Luvisols are widespread, e.g. in the German loess regions. These Luvisols are characterized by clay transfer processes from upper (elluvial) to lower (illuvial) horizons. This is very important for archaeological research questions because of their nearly constant thickness. The average thickness usually reaches around 40–50 cm for the elluvial and 50–70 cm for the illuvial horizon. Depending on the morphological situation the original soil profiles have changed due to forest clearing and the use of hills and other exposed terrain for agriculture, where erosion processes start. The large variation of current soil types in hilly areas is a result of human influence through agricultural activity over the last 6000 years. In some cases no remains of the original soil profiles were preserved, which means that more than 1 m of soil was lost by erosion. Eroded material will be deposited in depressions and at slope foots. A pedological survey can result in a soil map that shows the present distribution of these different kinds of soils. Assignment and depth of soil horizons and type and the determination of soil colour, content of organic material and carbonates and the moisture level are the most important parameters to be gathered by fieldwork (Behm et al., 2011). Areas of archaeological sites and their surroundings, which are strongly influenced by erosion, can be detected by soil mapping, as well as the accumulation zones, where sites are protected by a cover of colluvial deposits. Specific protection strategies can be developed in connection with land owners and the farmers by delineating erosion zones and erosion amounts.

Two case studies from the loess-covered hilly area northwest of Dresden in the surroundings of the small town Lommatzsch in Saxony will be presented in the following to exemplify our approach and the research method.

2.1 Case study Piskowitz-Tanzberg

Piskowitz-Tanzberg is a large area situated on a hill and attached ridge with pits and ditches of the Linear and Stroke-Ornamented Pottery Culture, as well as with burials of the late Bronze Age, early Iron Age and Roman Iron Age. The site is situated to the west of the hamlet Piskowitz. It was discovered during arable farming and was partly excavated by Johannes Deichmüller between the years 1905 and 1909. Since that time more than 100 years of agricultural land use has occurred there, and the question arose as to where it is still possible to find preserved burial remains (Behm et al., 2011).

Based on hand drillings and mapping, the analysis showed a compartmentalized mosaic of different areas of soil preservation. Promising areas with less erosion and hence potential for archaeological features could be identified. These are distributed at the nearly flat crest, where less (Le′) or a little more eroded Luvisols (Le$^+$) occur (Fig. 3). There, east of the top, a later excavation was successful and revealed some burial remains. To the north and west, we found calcaric Regosols (pararendzinas) and calcaric Cambisols (coloured in lilac and brown) that mark areas with a nearly complete erosional loss of the original soil profiles (Ender et al., 2012). In the east, larger parts of the area were covered with colluvial deposits (coloured in orange). In the north-eastern section, a small area with total profile loss can be recognized (coloured in lilac). From there to the south, a thin cover of colluvial deposits lies above brown soil. That brown soil indicates a former phase of erosion.

Soil profiles are not the only way to obtain information about the extent of erosion. The depth of the calcareous layers can also indicate it because the loess has high lime content. But calcaric components are leached and transported to lower parts of the profile during soil development. Therefore, the line of decalcification in developed Luvisols could usually be observed at a depth of about 1.20 m or more. In areas where profiles are shortened by erosion, the calcareous parts are closer to the surface, depending on the amount of eroded soil. In the case of pararendzinas and calcaric Cambisols, the substrate on top includes lots of calcaric components.

The evaluation of this site showed that a complete loss of the original soil profile can be observed and that the preservation at the central ridge and hilltop is rather endangered in some areas. Widespread ceramic findings in the plough horizon are also a sign for the ongoing destruction of archaeological remains. Therefore, a negative prediction for the future development needs to be given for most parts of the site. Our recommendation to protect the archaeological remains is that farmers should cultivate crops with a high degree of soil covering and implement consequent mulch tillage (Strobel et al., 2009).

2.2 Case study Burgberg Zschaitz

The site Burgberg Zschaitz, well known for its ramparts and ditches, is situated on a wide plateau of a hill spur and adjoins directly to the small village Zschaitz. Several remains and findings date to Middle and Late Neolithic, Late Bronze and early Iron Age. The two impressive great ramparts were constructed in Early to High Middle Ages. The rampart and ditch system separates the spur from the plateau and divides the area into an inner and outer bailey (Bromme et al., 2010). Soil mapping of the inner bailey showed that the soil profiles are completely destroyed. Only parts of the formerly very deeply buried archaeological remains are still preserved. This is due to soil erosion as a consequence of intensive agricultural land use on the one hand and man-made plantations during the Middle Ages on the other hand. Shifted soil material was deposited around the inner bailey in the north-west and south to build a rampart. The height of the main rampart in the east of the inner bailey was measured exactly during the 1950s. The comparison with a current measurement showed that during the last 60 years the rampart has levelled by about 60 cm due to agricultural use and ploughing (Bens et al., 2012). Moreover, the large number of archaeological findings in the plough horizon indicates rampart destruction.

The preservation state of the inner bailey and the main rampart is very poor. Fortunately it was possible to take this area out of agricultural land use and to convert it to grassland. To obtain this result, the land had to be purchased on behalf of the preservation of sites of historic interest and nature protection. An intensive cooperation between the administration, NGOs and private landowners was necessary to realize this preservation concept.

3 Protecting sites in farm- and wetland

3.1 Solutions to protect sites in farmland

Land use such as grassland delivers the best site preservation because barely any soil erosion occurs, and no farming machines disturb deeper soil layers. Several possibilities exist to take an area with archaeological remains out of agricultural farming and ploughing, such as (i) the land purchase of archaeological cultural monument sites, (ii) the swapping of areas with field areas without archaeological remains or (iii) the financial support of pasture management. In cooperation with the departments of nature conservation, soil protection, land consolidation or road construction, archaeological sites can be used as compensation areas. Compensation measures, such as the growing of green spaces to preserve nature and landscape, are demanded when construction projects use space. Such extensification solutions are not often realisable; however it is important to test all possible options to convert farmland with archaeological sites into grassland (Kretschmer, 2016).

Another protection measure is to apply no-till methods with specific and commonly available machines. These machines reduce the risk of soil erosion by leaving plant remains on the soil surface after harvesting and covering the top. Sowing new crops can be done by mulch tillage or direct seeding without tillage. The costs for purchasing such machines could be reduced by governmental incentives.

Both pasture management and conservation soil tillage are the only measures that protect the archaeological record as a permanent solution by excluding deep ploughing after any change of agricultural management.

Invisible archaeological monuments that are at risk from ploughing could also be covered, or the terrain could be filled with additional sediments or soil material, depending on soil conservation requirements.

Last but not least, technical equipment for arable farming has developed very fast during recent years, e.g. precision agriculture with GPS and newly constructed field machines for special functional requirements. Precision farming allows the protection of archaeological sites to be managed by treating these areas differently from other parts of the same field. Shapes of archaeological monuments can be seen on computer screens on board the machine. If the tractor reaches the site the cultivator may automatically lift to continue with more shallow tillage, preventing artefacts from being pulled out of deeper layers (Kretschmer, 2014).

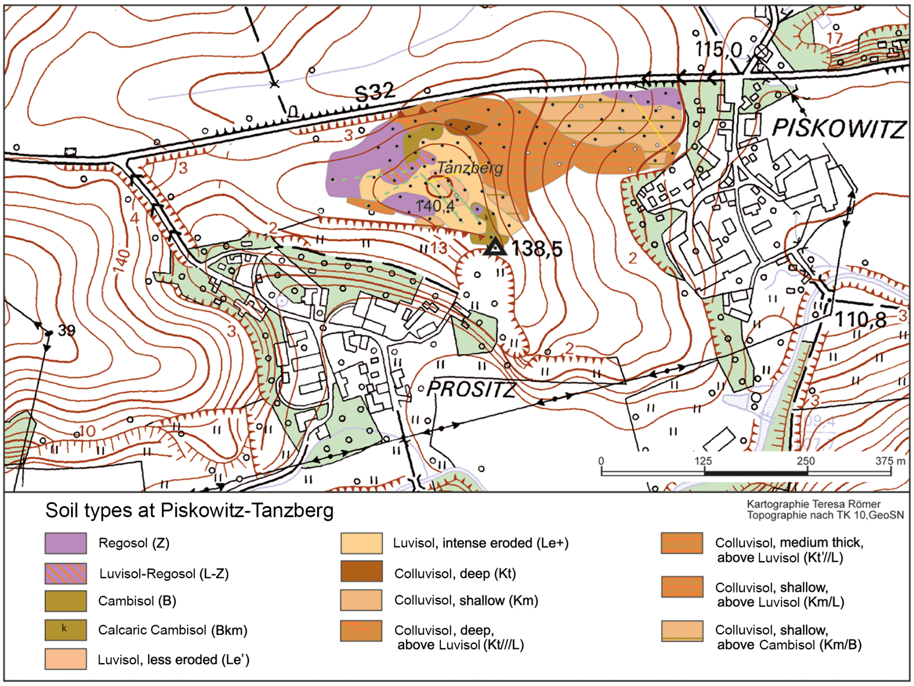

Figure 3. Detailed soil map of the surroundings of the site Piskowitz-Tanzberg (Saxony) (LfA Sachsen, T. Römer/R. Vogt).

3.2 Endangered wetland sites

Archaeological sites are not only threatened by agricultural use on farmland. Numerous bogs were meliorated in the past to obtain more and better grassland. Ditches or pipes were constructed to drain such areas. Descending groundwater levels resulted in humification and mineralization of peats, which often includes organic archaeological remains (Fig. 4). Thus, important information and archaeological remains could be destroyed, like famous sites of pile dwellings as well as wooden plank roads or outstanding findings like the 5000-year-old wooden disc wheels from the sites Alleshausen and Olzreute in Baden-Württemberg.

Organic material can survive thousands of years due to special preservation conditions under water and in an oxygen-free environment. The information content about pile dwellers' lives in the past and their related environment is inestimable (Aichele et al., 1999). This is why pile dwellings of six countries received UNESCO world heritage status in 2011. Most German sites are found in the south-west around Lake Constance and the Federsee region in Upper Swabia.

An area of nearly 400 ha of bog in the Federsee region was bought by the government of Baden-Württemberg to preserve archaeological cultural monuments for the future and to generate better conditions in this nature reserve. Ownership allowed the possibility to raise the groundwater level in this zone by building weirs and closing ditches. The original bog water supply could be restored, and preservation conditions of the archaeological sites were enhanced (Möllenberg and Schlichtherle, 2013).

Figure 4. Wooden disc wheel in the wetland site Olzreute-Enzisholz (Baden-Württemberg) beside wooden house construction elements (LAD, Baden-Württemberg/W. Hohl).

Yet, bog melioration remains a problem in other places. The Bodnegg site in the Allgäu region, discovered in 2014, serves as a good example. A fireplace with stony and loamy material was excavated beneath the dry soil surface. Settlement structures on this site were built on peat around 3900 BCE. This peat today has been totally transformed by the influence of oxygen in its upper parts because of the lower groundwater level. Thus, wooden parts of the houses and non-carbonized organic remains of the cultural layers have only survived in the lower parts (Ebersbach et al., 2017). Special protection strategies for such places need to be developed in every region.

4 Conclusions

The preservation of archaeological sites is endangered by many different effects of agricultural use, such as the deep ploughing of soils during cultivation, soil migration by machines, soil erosion by rainfall, drying wetlands by decreasing water levels or by the use of pesticides and fertilizers.

It can be shown that every site is different from another and inhomogeneous in itself. Therefore, an individual evaluation and development of solutions is needed for every single archaeological site. A joint concept for solutions and for protection strategies is necessary, incorporating the interests of landowners and farmers (Strobel et al., 2009). To obtain good results, many stakeholders from different departments need to be involved: agriculture, forestry, heritage management, nature conservation, sustainable soil protection and land consolidation (for more information, see, for example, https://www.denkmalpflege-bw.de/fileadmin/media/denkmalpflege-bw/publikationen/infobroschueren/informationen-praktische-denkmalpflege/10_archaeologie-landwirtschaft-forstwirtschaft/Broschuere_Archaeologie-Landwirtschaft-Forstwirtschaft.pdf (last access:14 December 2018).

Every single method helps to preserve the archaeological heritage, yet maximum protection is usually not achievable.

Data availability. All raw data of the drillings are stored at the Landesamt für Denkmalpflege im Regierungspräsidium Stuttgart (Richard Vogt) and can be obtained upon reasonable request.

Author contributions. RV carried out the fieldwork (drillings, observations and descriptions). The manuscript was written by IK and RV.

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