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QUATERNARY LANDSCAPES, SEDIMENTS AND GEOARCHIVES IN NORTHEASTERN GERMANY

A guidebook to fieldtrips on geology, geomorphology, geoarchaeology and climate and environmental monitoring

Guest editors: Achim Brauer and Markus J. Schwab

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Top: Lake Tiefer See in the Nossentiner/Schwinzer Heide viewed from north (Photo: A. Brauer)
Bottom left: Eastward view into a sandpit showing a kame terrace east of Lake Templin (Photo: B. Dieckmann)
Bottom center: Monitoring platforms installed on Lake Tiefer See (Photo: A. Brauer)
Bottom right: Northward view across the Large Mire of Ferch (Photo: B. Dieckmann)

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Preface: Quaternary landscapes, sediments and geoarchives in northeastern Germany – a guidebook to field excursions

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This special issue is a guidebook for five field excursions in NE Germany scheduled for the DEUQUA 2022 conference in Potsdam entitled “Connecting Geoarchives”. These excursions encompass a variety of different topics including quaternary geology, geomorphology, geoarchaeology and geoarchive monitoring. Four of these excursions will introduce different regions in the state of Brandenburg, while one will lead to the state of Mecklenburg-Vorpommern. Two excursions will present and discuss ice dynamics, geomorphological features and dating in the southwestern sector and southern margin of the maximum ice advance during the Weichselian glaciation. One has a focus on geomorphological and periglacial features and cultural heritage aspects in the area around Potsdam. Finally, two contributions will address more specific topics including new geoarchaeological findings in the mining region of Lower Lusatia and field monitoring for lake sedimentation and tree growth to trace climate signal transfer into these geoarchives. The target regions of the five field excursions are indicated on the geological map (Fig. 1).

Brandenburg is a classical region for Quaternary research because its geology is dominated by a large variation in different sediment types deposited during the succession of glaciations in the Pleistocene (Stackebrandt, 2018; Stackebrandt and Franke, 2015; Stackebrandt and Manhenke, 2004). These glaciations also shaped the landscape, and the margins of the Scandinavian Ice Sheet (SIS) at its largest extent were located in Brandenburg several times during the last 300 000 years. A striking piece of heritage of these ice advances is, for example, the Weichselian end moraine complexes. Since the first descriptions of these morphological remnants of the ice advances (e.g. Berendt, 1887), more than a century of research has revealed an increasing understanding of the glacial and postglacial landscape evolution. However, due to difficulties in dating glacial deposits and landforms, several questions remained unsolved. Only in the last decade with new methodological developments, for example, in cosmogenic nuclide and luminescence dating, has Quaternary research experienced a new boost, stimulating lively discussion. Based on these methodological developments, new concepts about the ice dynamics, especially during the last glaciation in the Brandenburg region, are discussed that reveal a larger complexity of the dynamics of the SIS than previously assumed (e.g. Böse et al., 2022). In addition to the progress in classical Quaternary research, new developments in the application of geoarchives in these Quaternary landscapes open new perspectives for also reconstructing the postglacial climate and environment evolution in the region, including the increasing role of humans in shaping the landscape. This volume combines these aspects with novel approaches in classical Quaternary research.

The ice margin of the maximum extent of the SIS during the Weichselian glaciation, known as the Brandenburg phase, is one of the focal points in this volume and target area of two

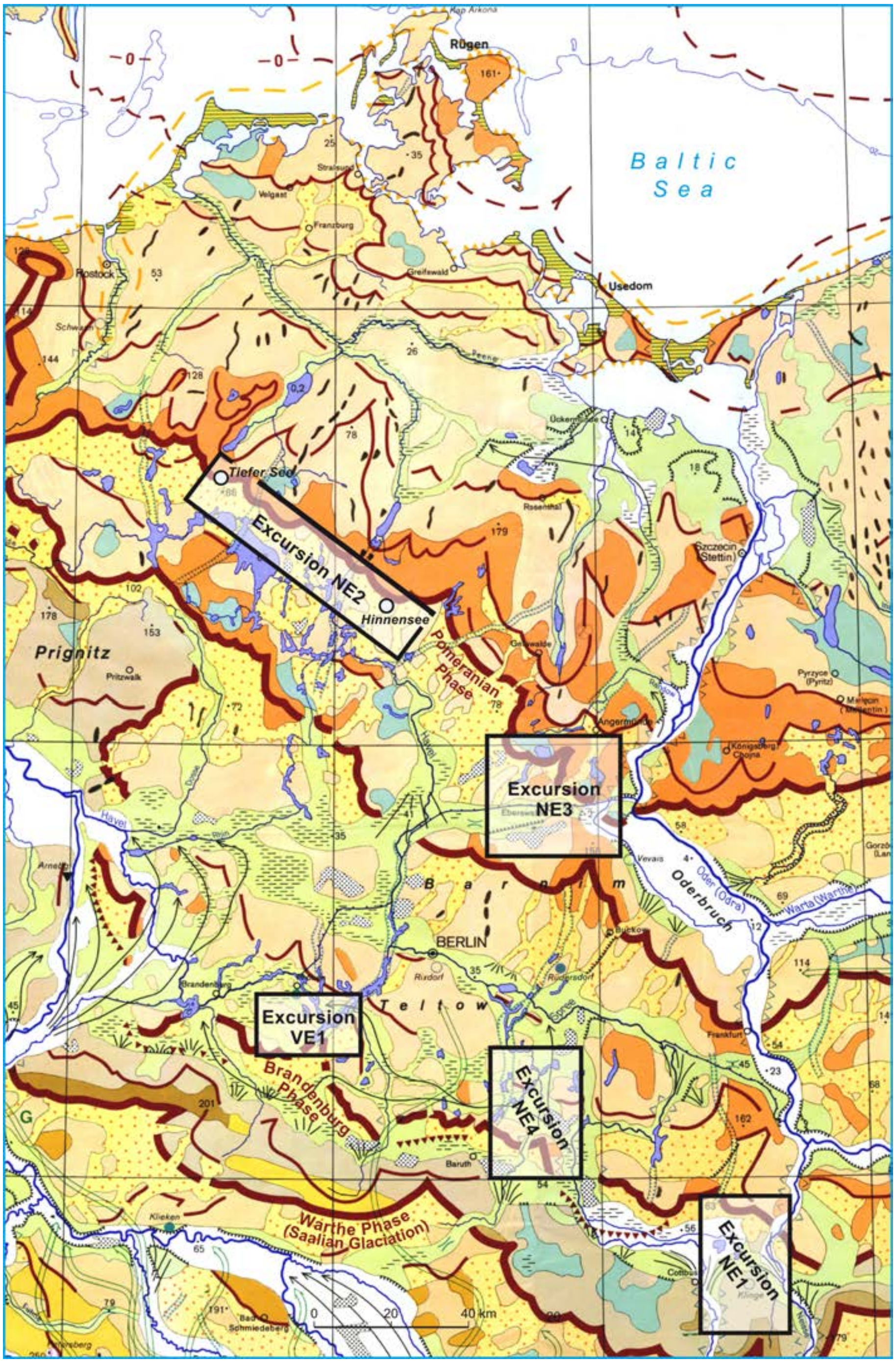

Figure 1. Location of the areas of the five field excursions presented in this volume. Background map is cut out and modified from the map *Die nordischen Vereisungen in Mitteleuropa* (Liedtke, 1981).

field excursions. Furthermore, the Telegrafenberg, location of the host of the DEUQUA 2022, the GFZ German Research Centre for Geosciences, is also part of the morainic complex of the Brandenburg phase.

The first excursion to this morainic complex in the vicinity of Potsdam is a guide through the region around the River Havel waters of lakes Templin and Schwielow (Diekmann et al., 2022) and will present local ice dynamics during the maximum ice advance as well as deglaciation and glacio-fluvial processes. In addition, cultural aspects will be also addressed since Potsdam and its surrounding areas were declared a UNESCO World Heritage Site in 1990.

The other field excursion presenting sites formed during the Brandenburg phase leads to the southeast of Berlin, an area where the SIS reached its furthest southern extent during the last glaciation (Juschus et al., 2022). In this region meltwater processes during the deglaciation played an important role in shaping the landscape and thus are in the focus of this field excursion. In addition, the final shaping of the landscape during the Holocene will also be shown and discussed.

The third chapter provides an introduction for a field excursion in the classical region of Quaternary research in northern Brandenburg and especially the Eberswalde–Chorin area (Lüthgens and Hardt, 2022). This region was shaped by the younger Pomeranian ice advance. Dating glacial sediments and terminal moraines has been a crucial challenge in Quaternary research (Hardt and Böse, 2018), and new developments in dating techniques that have led to new concepts of ice dynamics in the southwestern sector of the SIS (Lüthgens and Böse, 2011) will be discussed.

The fourth chapter also introduces a field excursion in the region of the Pomeranian terminal moraines but further to the west in Mecklenburg and with a different thematic focus (Brauer et al., 2022). Two long-term monitoring projects on different geoarchives are presented. As part of the Helmholtz TERrestrial ENvironmental Observatories (TERENO) infrastructure initiative, a lake and a tree-ring observatory have been in operation for about a decade (Heinrich et al., 2018) with the aim of tracing climate signal transfer into these archives of past climate and environmental variability with seasonal resolution. The instrumental setup and monitoring data are presented in this chapter.

The fifth chapter guides the reader to a region in Brandenburg south of the influence of the Weichselian glaciation (Hirsch et al., 2022). In Lower Lusatia, opencast lignite mines provide unique insights into human-induced environmental changes and thus add this increasingly important aspect to our understanding of Quaternary landscape dynamics. The focus of this chapter is on remains of historical charcoal production and their potential for landscape change.

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Quaternary geology and landforms around Potsdam by bike

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1 Introduction

The bike excursion around the river Havel waters of Lake Templin and Lake Schwielow follows routes and sites introduced in a set of former field guides, treatises, and maps, dealing with the natural and cultural heritage of Potsdam and its surrounding areas (Kramm, 1989; Weiße, 1995, 2001, 2012a, b; Grunewald and Marcinek, 1995; Rowinsky, 1995; Schroeder, 2001; Böse and Brande, 2002; Hermsdorf, 2005; Lutze, 2014; Stackebrandt and Franke, 2015; Stackebrandt, 2020). Most of the explanatory texts and illustrations have been published in German and are adopted here for the given background information and description of stops. Some of the figures have been modified, as referred to in the captions. In 1990, Potsdam was declared a UNESCO World Heritage Site of parks and palaces along the idyllic lakes of the Havel River, and it is a grand and historical city of culture and science (Horn, 2005; Lange, 2016). The bike tour highlights some aspects of the natural and cultural heritage of the Potsdam area.

2 Regional geological and geomorphological setting

The Quaternary geology and landscape of Brandenburg, comprising wide areas of the northern German lowlands, were basically shaped by the last three glacial and interglacial cycles during the Middle and Late Pleistocene (Schroeder et al., 2001; Lippstreu et al., 2015; Böse et al., 2018; Stackebrandt, 2020). Roughly about 95 % of Brandenburg is covered by loose sediments of glacigenic, fluvioglacial, alluvial, limnic, and palustrine origin, reaching thicknesses of more than 500 m in deeply incised troughs of the Elsterian Stage. These deep valleys were generated not solely by exogenic erosion but also by preceding neotectonic movements that prepared troughs for the accommodation of thick preglacial soft sediments, easily eroded by glacial action (Stackebrandt, 2009). The present landscape of Brandenburg from south to north is occupied by morainic belts and meltwater deposits of maximum advancing and decaying ice masses of the Scandinavian Ice Sheet during the Saalian and Weichselian stages, separated by large ice-marginal valleys (*Urstromtäler*) that drained the proglacial meltwaters from northerly directions as well as the rivers from the south towards the northwest (Fig. 1).

A reliable understanding of the right chronological order of the ice-marginal stages still suffers from contradictory dating results. Traditional approaches invoked morphostratigraphic correlations and the dating of organic matter included in interglacial and interstadial sediments under- and overlying sediments of morainic materials (Cepek, 1965; Lüthgens and Böse, 2012; Lippstreu et al., 2015). With growing progress in exposure dating techniques, such as optical stimulated luminescence (OSL) and surface exposure dating (SED), it became possible to also date glacigenic and glaciofluvial deposits directly related to the timing of ice-sheet dynamics (Brauer et al., 2005; Lüthgens and Böse, 2012; Hardt and Böse, 2016). The latest findings show that ice margins were not a static feature in time, as suggested by morphostratigraphic interpretations, but revealed marked diachronous behaviour both at a regional scale (Böse et al., 2018; Lüthgens et al., 2020) and for the entire Scandinavian Ice Sheet (Hughes et al., 2015).

The hills of the Fläming region together with the Lusatian border wall (Lausitzer Grenzwall), situated about 50 km south of Potsdam, reach the highest elevations in Brandenburg (140 to 200 m a.s.l.) and represent the morainic remnants (*Altmoränenlandschaft*) of the Warthe Stage (Marine Isotope Stage (MIS) 6) of the Saalian glaciation (Lippstreu et al., 2015; Meschede and Warr, 2019). Although the morainic surface is very smooth, lobes of differing end moraines and block chains appear beneath the periglacially formed ground layer. Exposure dating suggests formation of the Saalian ice margin between 170 and 150 ka (Krbetschek et al., 2008; Rinterknecht et al., 2012). In contrast to younger glacial belts, the Fläming landscape is barren of any lakes but was covered by aeolian sandy loess, creating a NW–SE-striking belt.

The area around Potsdam was basically shaped by glacial advances during the late Weichselian Brandenburg Stage, corresponding to the local Last Glacial Maximum around 24 ka (Böse et al., 2012; Hughes et al., 2015). The latest OSL data from meltwater sediments challenge this dating and provide older ages of between 34.0 and 27.0 ka (Lüthgens et al., 2010a, b, 2020).

The Frankfurt substage ice margin north of Berlin likely is represented by several younger recessional stillstands of the Brandenburg advance (Hardt et al., 2016). The youngest glacial advance in Brandenburg is documented by the Pomeranian ice margin that occupies the northeastern part of Brandenburg. Dating results range between 15 ka (Litt et al., 2007) and 20 ka (Lüthgens et al., 2011; Hardt and Böse, 2016).

3 Natural and cultural heritage of the Potsdam area

Situated between the wide glacial spillways of the Berlin and Baruth ice-marginal valleys, the area around Potsdam lies in the reaches of the Brandenburg ice-marginal stage. The area is characterized by a complex mosaic of morphological plates, morainic ridges, and lowland valleys (Weiße, 1991; Stackebrandt and Manhenke, 2004; Hermsdorf, 2005; Lutze, 2014) (Figs. 2, 3). This morphological configuration is not consistent with a simplified glacial-series concept. Strong overprinting was generated by dead ice, meltwater, and permafrost, creating a kame topography (Weiße, 2012a, b). Likewise, it seems that Late Pleistocene glaciation was routed by the preformed underground structure, created by neotectonics and former glaciations (Stackebrandt, 2009; Lippstreu et al., 2015). In analogy to the southeast orientation of the Nuthe River valley and the southwest elongation of the modern Havel River, two prominent palaeodepressions cut about 150 m below the surface into Neogene sediments at 120 m below modern sea level. Between the two palaeo-depressions a common Quaternary sequence can be found (Fig. 4). Depositional infills of the depressions comprise sediments of the last 440 kyr, with glacial tills and meltwater sediments of the Elsterian, Saalian, and Weichselian stages, as well as intercalated organic muds and peats of the Holsteinian and Eemian interglacials and of the Holocene. Mainly late Weichselian and Holocene sediments cover the modern landscape around Potsdam. Locally, outcrops of older deposits occur in morphological plates, which often include a core of basal tills of the Saalian glaciation (Fig. 3).

During the late Weichselian glacial maximum, the ice sheet reached 125 to 200 m thickness north of Potsdam (Weiße, 2012a). Bulldozing processes by the advancing ice lobes created a set of lateral and terminal push moraines, made up of compressed, imbricated, and folded proglacial sands and older tills. Today, they represent the highest morphological ridges and peaks around Potsdam (80 to 125 m a.s.l.), often fringing the margins of the plates. In places, thin, up to 4 m thick layers of basal till of this advance are preserved as ground moraines on the plates. Glacial advance around Potsdam was driven by two ice lobes. One of those traversed the Nuthe Valley in a westward direction; another one filled the Havel River valley and moved in a southward direction (Weiße, 1991; Hermsdorf, 2005). During its maximum extent, the ice sheet with its different lobes reached nearly the northern slopes of the Fläming Hills south of the Baruth ice-marginal valley and then retreated to the north (north of the then active Baruth ice-marginal valley), where they formed a stagnating ice margin, which nonetheless was not persistent in space and time (Juschus, 2010; Böse et al., 2018). During that time, the ice lobe filling the Havel depression scoured the underground down to 60 m below the present-day surface, by both glacial exaration and strong subglacial meltwater erosion. Sediment-laden melt-

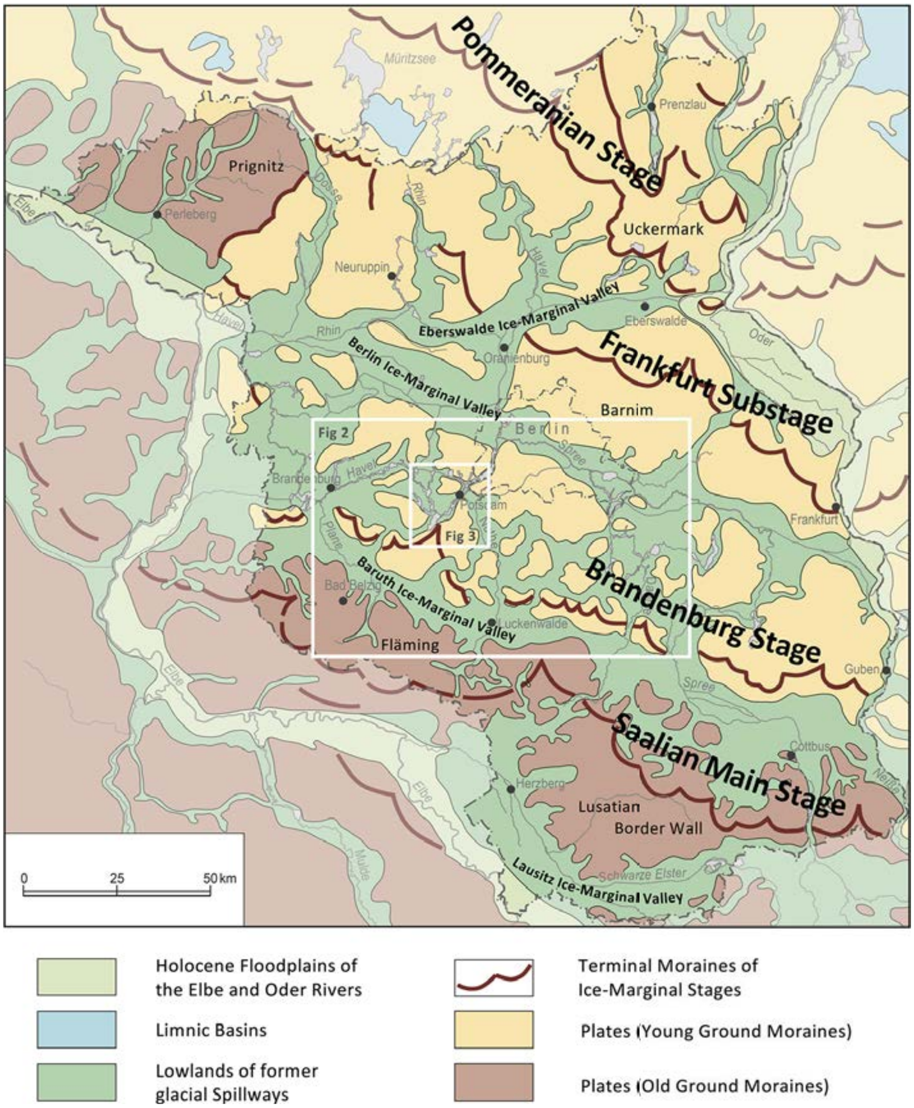

Figure 1. Geomorphological units of Brandenburg (modified after Stackebrandt and Franke, 2015; Stackebrandt, 2020). Insets show the positions of the maps in Figs. 2 and 3.

water from subglacial tunnels of that lobe fed a huge, 70 km^2 proglacial outwash cone (sandur, *Sander* in German), which passes over at its marginal fringe into the Baruth ice-marginal valley. The so-called "Beelitz Sander" is located about 20 km south of Potsdam (Figs. 2, 5).

During deglaciation, ice-sheet retreat and disintegration led to the isolation of motionless ice fields and blocks in the northern hinterland of the former ice margin (Weiße, 1991, 2012a, b). The collapse of subglacial valleys sealed meltwater channels by dead ice (Juschus, 2010). The glacial sediments carried by meltwaters were deposited on and between the ice remnants. During final deglaciation, they left behind kame hills and kame terraces with ancient ice-contact slopes. Except for a few dead ice relics preserved by overlying sediments, ice decay was likely completed at the latest during Bølling–Allerød warming, roughly between 15.0 and 13.0 ka. This time was characterized by boreal climate conditions and the growth of birch and pine woodlands (Rowinsky, 1995; Wolters, 1999; Brande and Rowinsky, 2017). Glacial decay significantly changed the drainage path of meltwater flow away from the Baruth ice-marginal valley towards the northern hinterland of the former ice margin (Juschus, 2010). With its height of 70–80 m, the Beelitz Sander became a topographical barrier and diverted meltwater discharge to the neighbouring Kanin Valley (Kaniner Tal; 40–60 m a.s.l.) (Böse and Brande, 2002) (Fig. 3).

With ongoing unsealing of the local lowlands, other meltwater routes followed the Nuthe depression to the northwest, the Havel depression to the southwest, and in a westward direction the valleys west of Potsdam (Weiße, 2001, 2012a).

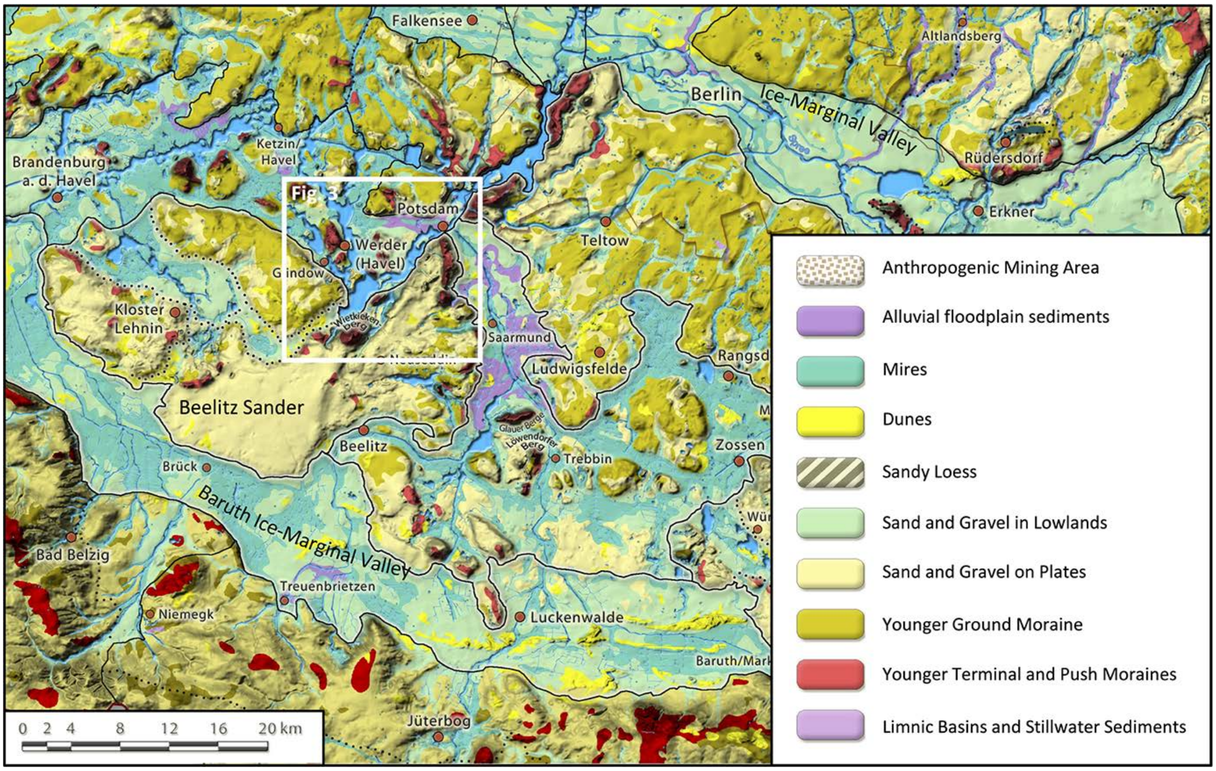

Figure 2. Geological map of the wider surrounding of Potsdam (modified from Lutze, 2014). Inset shows position of the map in Fig. 3.

During the late glacial Younger Dryas, climate deterioration caused a return to subarctic conditions, dominated by waterproof permafrost ground and periglacial processes (Weiße, 2001). Dry valleys and screes formed along steep slopes, while surficial soils and sediments were affected by cryoturbation and ice-wedge growth. Dryness and a sparse vegetation cover gave rise to aeolian sediment remobilization and the transformation of dune fields (Kaiser et al., 2009). Nevertheless, as a consequence of medieval German settlement and deforestation, a reactivation of sands by aeolian processes caused the formation of dunes on the southern part of the Glindow plate close to Bliesendorf, burying the Holocene brown soil (Brande et al., 1999; Böse et al., 2002).

Today's temperate climate and modern environment developed during the Holocene. The last remains of dead ice finally melted out. Lake basins, modern river courses, floodplains, and wetlands occupied the valleys, while small hollows were filled with ponds and mires (Wolters, 1999; Weiße, 2001; Brande and Rowinsky, 2017). Mixed pine and deciduous forests expanded at the expense of pine woodlands (Wolters, 1999).

Anthropogenic land use in the Late Holocene changed natural landscape, vegetation, and hydrology around Potsdam (Böse et al., 2002; Viehrig, 2002; Rubin et al., 2008; Lutze, 2014). In particular, deforestation, pasture farming, the expansion of hunting grounds, fruit and wine growing, and damming, as well as peat and clay mining, left their tracks in the modern cultural environment.

After the slavonic settlements mainly founded from the 4th to the 8th century, a major rural transformation changed the aspect of the landscape with the German settlement from the 11th century onwards. The plates were widely cleared for agricultural purposes, using new ploughing techniques. The area southwest of Potsdam was predominantly influenced by the foundation of the Lehnin monastery in 1180 and the related villages in the surroundings (Böse et al., 2002). A major transformation in the river system and the adjacent lowlands was induced by the medieval German construction of watermills and consequent damming. The Potsdam area was mainly influenced by the dam built in Brandenburg in 1309, which induced a water-level rise of more than 1 m in the Havel system and a groundwater-level rise in the adjacent flat areas (Kaiser et al., 2017).

From the 17th century the Prussian regency started to design the landscape around Potsdam, characterized by parks and forests for hunting, the intensification of agriculture, development of infrastructure (canals, roads), and the expansion of settlement areas (Viehrig, 2002; Rubin et al., 2008; Lutze, 2014; Lange, 2016). The increasing demand for wood in industry, for building timber, and for firewood in the cities led to an acute shortage of wood in the 18th century. Soils became impoverished in nutrients such that they only allowed for the cultivation of pine trees. Efforts for reforestation in-

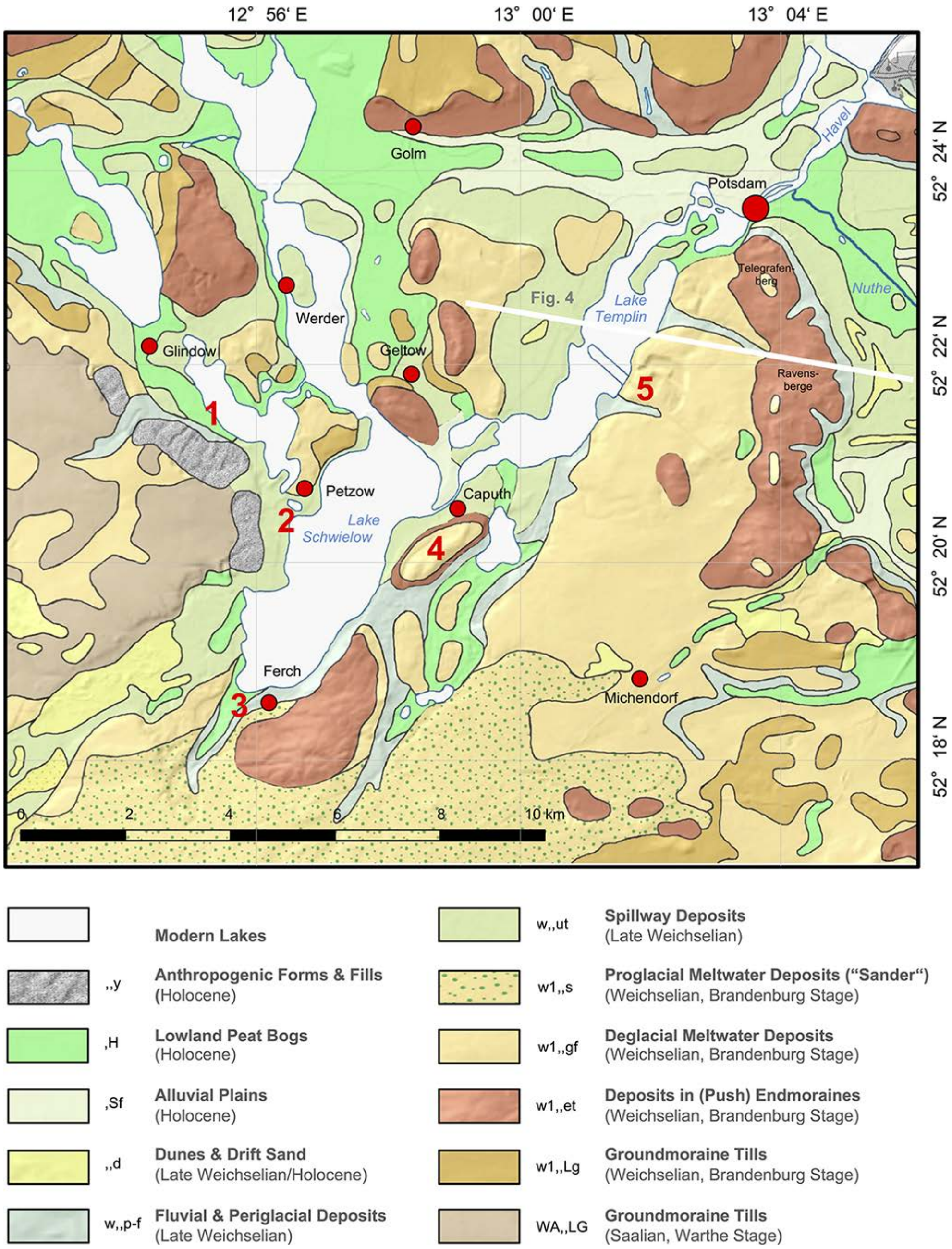

Figure 3. Geological map of the area southwest of Potsdam, redrawn from the 1 : 100 000 geological map of Hermsdorf (2005). The map is underlain by relief obtained from a DGM (*Digitales Geländemodell*, i.e. digital elevation model) of the Brandenburgviewer (LGB, 2020). Red numbers indicate the stops of the field trip. The white line shows the approximate location of the geological profile depicted in Fig. 4.

creased in the late 19th and early 20th centuries and in particular after World War II, leading to the widespread presence of pine forests in Brandenburg (MLUL, 2015).

Today, a variety of landscapes, geomorphology, soils, and hydrology are reflected in different forms of land use (Brande et al., 1999; Knothe, 1995; Lutze, 2014). Agriculture and fruit growing mainly take place on the plates with their glacial tills and sands that are covered by brown earth and para-brown earth soils with leak waters. The steep terminal moraines, outwash plains, and dune fields are mostly covered by forests; exposed southern slopes are partly covered with vineyards.

The valleys with groundwater fluctuations are used for agriculture or are covered by green land. Parks in and around Potsdam are often located on river terraces with sandy substrate underneath. The Beelitz Sander represents a famous

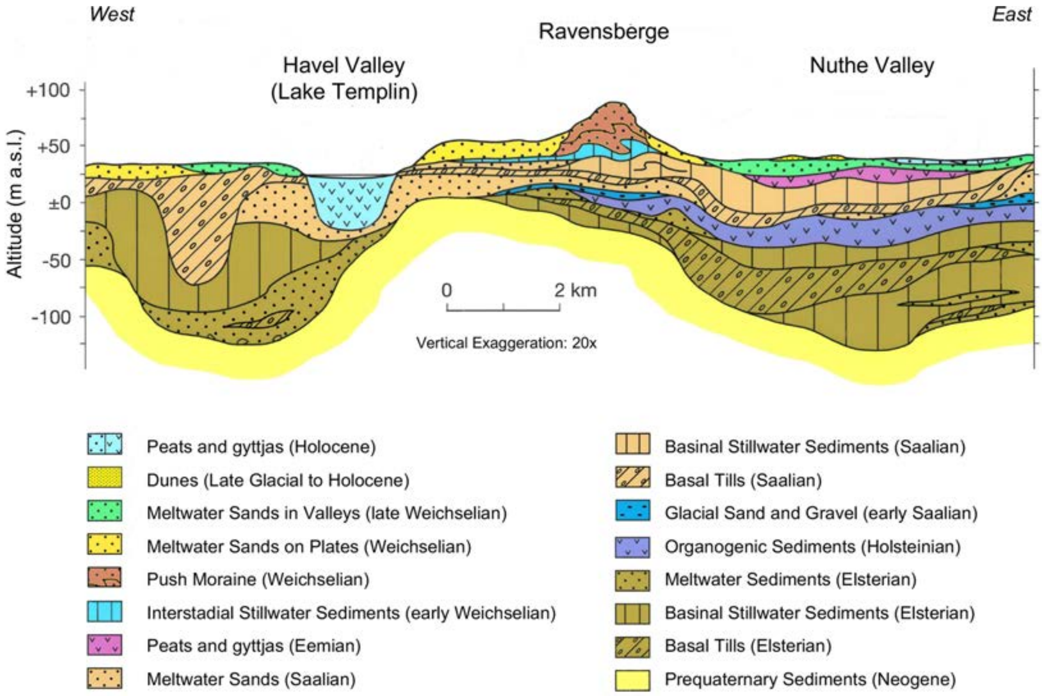

Figure 4. Generalized geological profile through the Quaternary sedimentary section of Potsdam (unpublished after Norbert Hermsdorf, Landesamt für Geowissenschaften und Rohstoffe Brandenburg, LGRB). Location of profile is shown in Fig. 3.

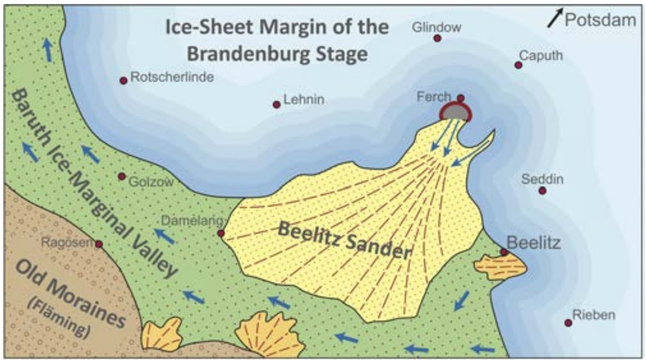

Figure 5. The outwash cone of the Beelitz Sander at the Weichselian ice margin south of Potsdam (modified from Stackebrandt, 2020).

environment for the cultivation of asparagus. The use of raw materials from natural substrates, such as peat, clay, and sand, play a role today and have done in the past.

In addition to raw materials, other resources relate to water management and the utilization of geothermal energy. Infiltration water of the Havel River including especially water from the second groundwater level located beneath an impermeable layer provides a rate of 8000 to 10 000 m^3 of potable water per day in each of the five waterworks, sufficient for the whole Potsdam community (180 000 inhabitants). The use of near-surface groundwater is influenced by saltwater brine, which is often bound to Elsterian glacial erosion zones as deep valleys (e.g. Nillert et al., 2008). Thermal influx from depth is already used for numerous geothermal heat pumps installed for the heating of single-family houses. Complex geothermal probe fields are being implemented or planned, which will also meet higher performance requirements.

4 Bike route

The bike tour stretches about 30 km around Lake Templin and Lake Schwielow, which are part of the open lake and river system of the Havel River (Fig. 3). It starts in the historical centre of Potsdam and follows in a southward direction the western shore of the Havel River. The side views give insight into the history and cultural development of Potsdam. The skyline opposite the river Havel follows the ridges of the lateral moraines of the Telegrafenberg and Ravensberge. The next stops highlight the glacial and postglacial development of the area and deal with geomorphology, land use, exploitation of raw materials, and cultural history.

4.1 Stop 1: Petzow

The scenic surroundings of the village of Petzow with its 400 inhabitants, embedded in a hilly kame landscape, highlight the intimate fusion of nature and culture, which is so typical of the wider Potsdam area (Weiße, 1995). First mentioned in 1419, the village with its present Brandenburg

Figure 6. Panoramic view from the tower of the village church of Petzow (52°20.74′ N, 12°56.52′ E) (photo: Bernhard Diekmann, 2022). The village of Petzow is hidden by trees to the left. The treeless plateau on the right side shows the surface of the Glindow plate to the southwest. The middle part offers an eastward view across the kettle depression of Lake Petzow with Lake Schwielow in the background. The glacial lobe of the Havel River valley terminates in Ferch at the southern end of the Lake Schwielow depression to the right. The hills on the opposite side of Lake Schwielow delineate the ridge of Wietkiekenberg (125 m a.s.l.), a push moraine at the ice-marginal position of the Brandenburg Stage, the highest elevation around the excursion route.

brickstone architecture was created during the early 19th century. A neoromantic church, erected by Karl Friedrich Schinkel in 1841, towers the village to the west. To the east, a palace in English Tudor style borders the village close to the shore of Lake Schwielow. The famous royal gardener Peter Joseph Lenné designed the idyllic, 15 ha castle park that surrounds Lake Petzow, a prominent kettle lake filling the depression between Lake Glindow and Lake Schwielow. A view from the tower of the village church offers a view across the adjacent glacigenic landscape (Fig. 6).

4.2 Stop 2: Glindow Alps

The area between Glindow and Petzow delineates the northeastern margin of the Glindow plate, basically a ground moraine of Saalian age, overlain by thin veneers of Weichselian tills and melt-out sands and gravel (Figs. 3, 7). Along the southwestern shore of Lake Glindow, interstadial lacustrine meltwater clays were deposited between tills of the Drenthe and Warthe stages and squeezed by glacial push, leaving behind contorted and imbricated layers of clay deposits (Dienemann, 1928; Weiße, 2012b). The NW–SE-oriented folds and slices are proof of a glacial tectonic compression from the northeast.

With the expansion of Potsdam and the neighbouring city of Berlin in the Wilhelminian era of the late 19th to early 20th century, the demand for building materials rose and the brick and tile industry experienced an unprecedented upswing. Around Glindow, glaciolacustrine clays (*Bändertone*) were exploited as raw materials (Fig. 7) in more than 10 pits that benefited from the water front position of the Havel lakes (Weiße, 1995, 2012b). Today, only one of the brick manufactories is in occasional operation and serves as a mining museum (Fig. 8).

Clay mining proceeded in trenches, after the non-clay substrates had been removed and piled to the side. The exploitation of the raw materials and redeposition of unusable sediments and soils created a human-made terrain of canyons, hills, and hollows, today known as the Glindow Alps. The renaturation of the area led to reforestation, the formation of valuable ponds for aquatic life, and the establishment of dry grasslands, serving as a natural reserve.

4.3 Stop 3: ice-marginal and postglacial landscape of Ferch

The village of Ferch with its population of about 1800 inhabitants is situated at the southernmost tip of Lake Schwielow, roughly 12 km south of Potsdam (Fig. 3). The area lies directly at the former ice front of the Brandenburg Stage (Rowinsky, 1995; Böse et al., 2002; Hermsdorf, 2005; Brande and Rowinsky, 2017). A 20 m high rise to the south of Ferch marks the transition to the outer sandy meltwater cone of the Beelitz Sander (Fig. 5). The sandur was fed through a glacier mouth (Fercher Gletschertor) by meltwaters of a subglacial channel, crossing the village of Ferch from NNE to SSW. Glacial retreat produced a kame landscape with elongated hollows and crests. The inner slope of the Beelitz Sander blocked and diverted the draining meltwater streams to the northwest through the subaerial Kanin Valley, which also hosts dune fields of possibly late glacial age (Fig. 3). The former subglacial channel was filled with 65 m of deglacial clastic sediments, graded into lacustrine and palustrine sediments that underlie the modern wetland

Figure 7. Open pit on the northeastern part of the Glindow plate (52°20.26′ N, 12°55.69′ E) (photo: Bernhard Diekmann, 2016), used for clay mining. Meanwhile, the exposure has been filled up and is no longer accessible.

Figure 8. Ring furnace of a brick manufactory in the Glindow Alps (52°21.3′ N, 12°55.4′ E) (photo: Bernhard Diekmann, 2020, with courtesy of the Brickyard Museum of Glindow).

of the Ferch valley (Rowinsky, 1995). Within the postglacial sequence a 2 cm layer of the aeolian Laacher See tuff was also found. In analogy, the small basins of the neighbouring kame terrain developed from kettle ponds to mires during the Holocene (Fig. 9).

4.4 Stop 4: Caputh

The village of Caputh (33 m a.s.l.) lies at the constriction of the locally channelized Havel River, connecting Lake Templin to the northeast with Lake Schwielow to the southwest (Fig. 3). Since 1853, a cable ferry has crossed the river course. Caputh, with its more than 5000 inhabitants, was first mentioned in 1317 and in the 19th century became an important spot of inland navigation for the shipping of bricks from the Glindow area. Historic buildings, such as the Caputh Palace (1662) and the church (1852), the latter built according to plans of the renowned architect Friedrich August Stüler, are eye-catchers in the centre of the village. In the last century, Caputh developed into a summer residence for wealthy families from Berlin and Potsdam. Between 1929 and 1932, Albert Einstein was a prominent visitor, who used

Figure 9. Northward view across the Large Mire of Ferch (52°18.35′ N, 12°54.88′ E), including about 10 m of gyttjas and peats of late glacial to Holocene age (Rowinsky, 1995) (photo: Bernhard Diekmann, 2020).

Figure 10. View of the eastern slope of Krähenberg in Caputh (52°20.4′ N, 12°59.3′ E), a kame landform that is built up of gravelly sands (photo: Bernhard Diekmann). The glacial granite boulder is of local origin and has been put there for decoration.

to spend his summer holidays (*Sommerfrische* in German) in a wooden mansion before he emigrated from Germany (Schwielowsee Tourismus, 2022).

The 500 × 700 m Krähenberg (85 m a.s.l.) rises 40 m above the lower part of the village of Caputh. The hill represents the northeastward continuation of the lateral moraine of Wietkiekenberg (125 m a.s.l.) in Ferch and shows signs of ice pressing at its base (Weiße, 2001). The upper sediments of Krähenberg consist of clast-bearing sands, interpreted as thaw sediments in a kame setting. Glacial clasts comprise the typical spectrum of Nordic origin with crystalline components and quartzite as well as chert and flint fragments from Scandinavia and the Baltic Sea. The sediments are well exposed on the steep eastern flank of the hill, covered by dry grasses and few trees (Fig. 10).

The top position on the hill offers a panoramic view across the glacial landscape around Caputh. The ridges of the Ravensberge (up to 114 m a.s.l.) towards the east mark the lateral push moraines of the Brandenburg Stage bordered to the west by a kame terrace of the meltdown stage (Potsdamer Heide, 70–80 m a.s.l.). The foreground to the east is occupied by Lake Caputh (31 m a.s.l.), directly located at the former ice-contact slope of the kame terrace. Lake Caputh as a typical kettle lake structure is part of a former (subglacial) meltwater valley heading towards the southwest. The Krähenberg and Wietkiekenberg axis apparently formed a morphological divide between the glacial lobe of the Lake Schwielow de-

Figure 11. Northward view along the eastern shore of Lake Templin with the former ice-contact slope and periglacial dry valley to the right (52°21.55′ N, 13°01.55′ E) (photo: Bernhard Diekmann, 2020).

Figure 12. Eastward view into a sandpit of the kame terrace east of Lake Templin (photo: Bernhard Diekmann, 2020). Image was taken from the western margin of the terrace (52°21.9′ N, 13°01.8′ E), close to Lake Templin.

pression located to the west and the valley of Lake Caputh. The background to the west shows the hummocky kame landscape at the western shores of Lake Schwielow around Petzow as well as the outflow of the Havel River to the northwest; in the background, the small town of Werder with adjacent fruit yards can be seen.

4.5 Stop 5: Lake Templin

The way back to Potsdam takes the road along the eastern bank of Lake Templin, which is bordered by a steep, 20 to 30 m high slope, documenting former ice contact at the margin of an extensive kame terrace, already seen in the background of Stop 4 in Caputh (Weiße, 2001; Hermsdorf, 2005). The up to 4 km wide outwash plain (60–75 m a.s.l.) formed during the meltdown stage between the morainic ridges of the Ravensberge (114 m a.sl.) and the Havel River (30 m a.s.l.) and stretches from Potsdam to Caputh (Figs. 3, 4). After final deglaciation, the ice-marginal slope was sculptured by periglacial processes, leaving behind dry valleys and gullies (Fig. 11). The adjacent Havel River is underlain by a postglacial basin, filled with up to 45 m thick gyttjas (Fig. 4).

The clastic sediments of the kame terrace represent important raw materials, which since the 1960s have been exploited for the building industry. A mining pit is located directly north of the railway track between the road to Michendorf and Lake Templin (52°21.7′ N, 13°02.3′ E) (Figs. 3, 12). Today, the outcrop situation is not satisfying for field description. Former studies have reported a more than 20 m thick section of fine- to medium-grained sands with up to 7 % gravel contents. Most of the sands are current-bedded, pointing to transport directions towards the remaining ice lobes to the west and southwest (Weiße, 2001, 2012a). Postdepositional faulting is a sign of sagging with the loss of ground ice and the meltdown of adjacent ice bodies.

The railway track through the sand deposits and across the Havel Bridge is part of the railway ring, constructed in the mid-1950s (Bley, 2016). It was a technical and engineering challenge because the Havel riverbed not only had thick layers of sludge but was also very inhomogeneous due to deep pools. The bog blasting method was used, by means of which the stabilizing sand fill could be brought down to the load-bearing subsoil by means of loosening blasting.

The road along Lake Templin leads us back to Potsdam, and the tour finishes at the base of the Telegrafenberg, which forms part of one of the pronounced push moraines of the Brandenburg Stage and is the venue of the DEUQUA Conference 2022.

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To the southern margin of the (last) northern glaciation – a field trip through the young moraine area south-east of Berlin

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Abstract: The young moraine area to the south-east of Berlin was repeatedly overrun and covered by Scandinavian ice sheets (SISs). The last glaciation took place during the Last Glacial Maximum (LGM), when the last/most recent SIS reached its furthest southern extent. An incompletely formed chain of terminal moraines marks the Brandenburg ice stage. The most recent glacier had its greatest environmental impact due to the large quantities of released meltwaters. Many subglacial channels, massive proglacial sands and huge meltwater streamways (*Urstromtäler*) were formed at that time. During the Holocene, the landscape was finally shaped mainly by the rivers Dahme and Spree.

Dedication. Dedicated to Norbert Hermsdorf (1961–2019).

1 Introduction

The field trip will take us to interesting sites of Quaternary geology and geomorphology to the south-east of Berlin. The stops will cover a wide range of different topics connected not only with the waxing and waning of the Scandinavian ice sheets but also with the history of the post-glacial landscape and human impact. During the field trip, we will visit outcrops with Quaternary sediments from different ice advances and morphological sites like the southernmost Weichselian terminal moraines of the Brandenburg phase (WB) as well as late glacial palaeochannels of the river Dahme (Fig. 1).

1.1 Historical overview

The geological exploration of this area close to Berlin began immediately after the implementation of glacial theory in Germany. Beginning in the 1880s, most sheets of the 1 : 25 000-scale geological map were being mapped by the geologists of the Prussian Geological Survey (in the late 19th century under the leadership of Berendt and Wahnschaffe, in the early 20th century under the leadership of Fliegel and Keilhack). Thus, the general composition of the Quaternary of the region was already known at the beginning of the 20th century. During the 1950s Genieser (1957) published on the Mid-Pleistocene gravels of the so-called Berlin Elbe River. After 1990 the investigations of Hermsdorf (1995) and Juschus (2001) are worth mentioning. Hermsdorf (1995) gave a summary of the general geological settings of the Quaternary in the area which still corresponds to the cur-

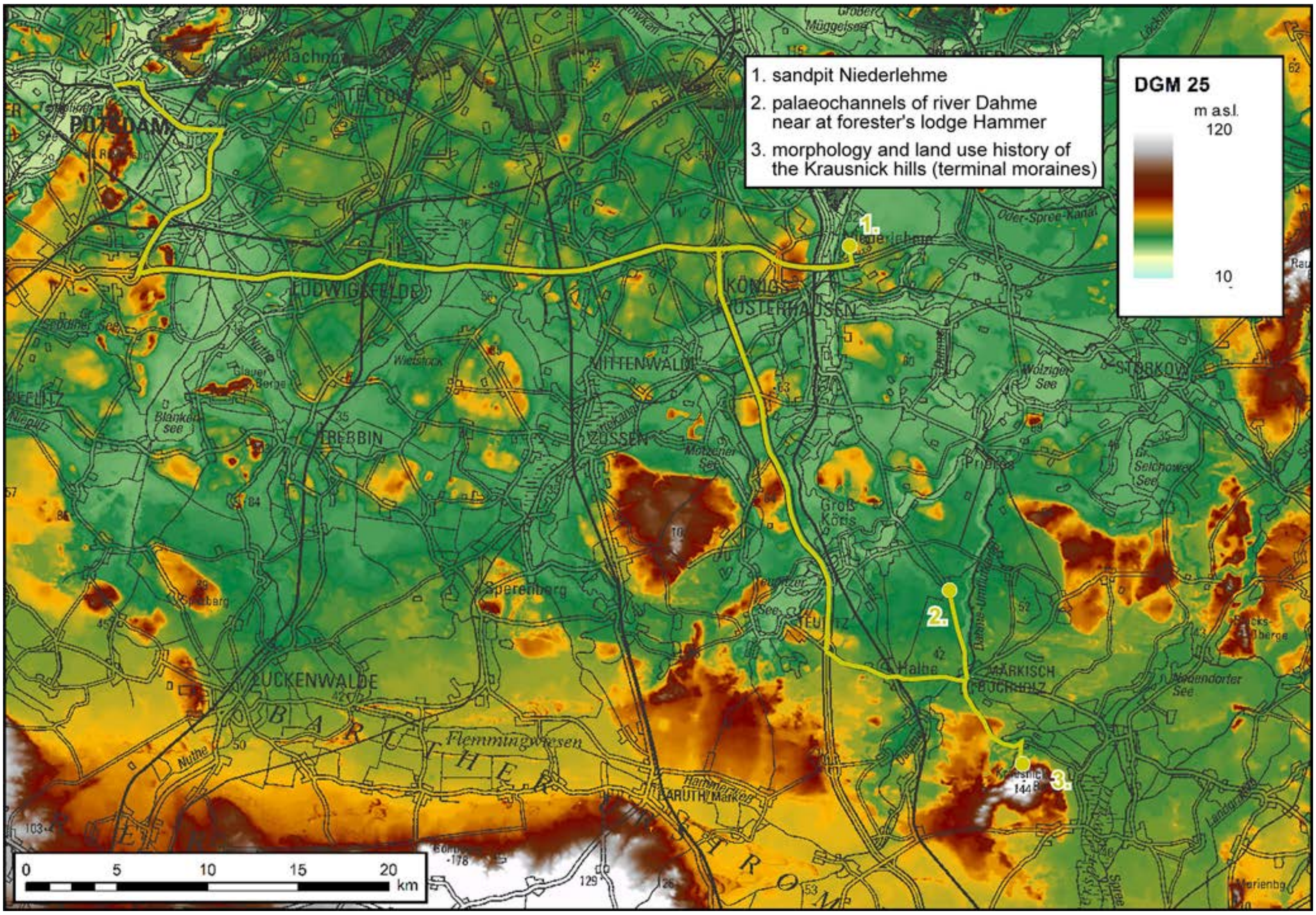

Figure 1. Overview, route and stops of field trip "To the southern margin of the (last) northern glaciation" (base map: Landesvermessung und Geobasisinformation Brandenburg). The raised, island-like Quaternary plateaus are visible within the elongated meltwater streamways. For distribution of morainic plateaus and meltwater streamways see also Fig. 4.

rent state of knowledge. Juschus (2001) was focused on landscape development during the Weichselian glaciation and the Holocene. A modern, 1 : 100 000-scale geological map of this region was published by Hermsdorf (2007).

Geomorphological investigations in this region have focused mainly on the course of the terminal moraines of the Brandenburg phase and the development of the Baruth ice-marginal valley. Following initial approaches by Berendt (1880), Lembke (1936) described the height relationships of the main valley and the adjacent run-off paths. Marcinek (1961) and Juschus (2001) added further findings, especially on the phased development of the Baruth ice-marginal valley. While Marcinek (1961) described two run-off phases, Juschus (2001) extended the model to up to four phases, to which different terrace levels are assigned. All four phases followed in a short time frame the maximum advance of the Weichselian ice sheet.

The time frame of the last ice advance was recently dated by the investigations of Lüthgens et al. (2010, among others). Using the OSL method, they determined an age (maximum age) of 34.1 ± 3.0 kyr. Litt et al. (2007) give an age estimate of between 20 and 24 kyr BP (based on extrapolations of calibrated ^{14}C ages in northern Germany and northern Poland).

1.2 General geological settings

The Quaternary sequence in the region starts with Elsterian deposits (Fig. 2). Older Quaternary sediments have not been described so far. The thickness of the Elsterian sediments varies within a wide range and is mainly determined by the occurrence of deep subglacial channels of Elsterian age. The base of the Quaternary deposits lies at between −75 and −500 m inside the channels and at −25 to −40 m outside them. Locally, the top of autochthonous Miocene sediments lies at around sea level. The Elsterian sediments are mainly preserved as channel infill. Outside the channels, they are relatively weak or completely absent. Usually, the Elsterian sediments consist of fine- and medium-grained sands, silty–clayey basin deposits, and till. Allochthonous packages of Neogene sediments are relatively common. The Elsterian stratigraphic sequence is characterised by relatively strong deformation features, mainly induced by gravitational mass movements and, more commonly, glaciotectonics.

The subsequent Holsteinian interglacial is characterised by its large horizontal and vertical distribution of commonly sandy to gravelly fluvial sediments. In between, several layers of silts and muds can be found. The fluvial activity continued after the end of the Holsteinian until the Saalian ice advances. These sediments were connected by Genieser (1957) to a precursor of the river Elbe.

Saalian sediments are composed of thick, partly gravelly proglacial sands, which are overlain by only one Saalian till. The complete absence of a second Saalian till still causes problems in correlating Saalian deposits with adjacent regions, where two till layers are common. Both a primary absence and a subsequent removal are conceivable. Based on indicator pebble analysis, there is some evidence that the occurring till was settled during the younger (Warthe) phase of Saalian glaciation. Strong glaciotectonic features are very common within Saalian deposits.

The surface of the Saalian sediments shows extensive weathering phenomena, which are attributed to the Eemian interglacial and the subsequent Early Weichselian period. In contrast to Holsteinian sediments, Eemian deposits are restricted to a number of small-scale basins.

The sediments of the Weichselian glaciation are mainly built up of sandy–silty or sandy–gravelly proglacial deposits, which often reach thicknesses of 10 to 15 m. With an average thickness of less than 3 m, the sandy Weichselian till is comparably thin and patchy.

Thus, the most recent glacial advance had its greatest environmental impact due to its large quantities of released meltwaters. Many subglacial channels, massive proglacial sands and huge meltwater streamways (*Urstromtäler*) were formed at that time. The streamways cover more than half of the area. Thus, the young moraine area to the south and south-east of Berlin is a patchwork of elongated meltwater streamways with raised island-like quaternary plateaus.

In addition to late glacial dune sands, Holocene muds and peats occur mainly as infills of Weichselian glacial channels.

2 Stop one: the Niederlehme sandpit

The sandpit near Niederlehme contains a succession of Quaternary deposits typical of the young moraine area to the south-east of Berlin. Due to its vicinity to Berlin, the profiles of the pit have been repeatedly investigated (e.g. Wahnschaffe, 1910; Cepek, 1986; Böse, 1997; Hermsdorf, 2000; Juschus and Błaszkiewicz, 2002).

At the bottom of the outcrop, deposits of Saalian age composed of heterogeneous material are found. Till is most frequent, but lenses of sand and silt are common as well. The till mainly consists of silt. As is typical of lower till, the boulders mainly originate from the ground of the Baltic Sea (north-eastern direction).

These older deposits are overlain by comparably coarse-grained glaciofluvial material, the so-called “Rixdorf Horizon” (Figs. 2, 3). These gravels contain bones of huge mammals (mammoths, woolly rhinos, etc.) as well as other remains of the old, proglacial landscape such as weathered rocks and ventifacts. The Rixdorf Horizon was formed by the initial Weichselian meltwaters, running from the south-east to north-west.

On top of the Rixdorf Horizon, there are thick proglacial sands with sparse lenses of silt or coarser material. These sands are the main target of the sand excavation. Excluding some periglacial deposits, the top of the sediment succession is formed by a thin and patchy till of Weichselian age. The pebbles inside this till originate mainly from eastern Sweden (northern direction). In contrast to the older Saalian till, the Weichselian till is dominated by a sandy matrix.

3 Stop two: late glacial to Holocene development of the river Dahme in the basin of Märkisch Buchholz

3.1 Introduction

The small town of Märkisch Buchholz is situated inside a huge basin area, mainly formed by meltwater streamways (Fig. 4). The valley-like character is somewhat blurred by the large extent of this basin (approx. 15 km in diameter). It has already been created as a deep-lying area during the Saalian glacial period. Decametre-thick glaciolimnic sediments were deposited in an ice-dammed lake, while the surrounding plateaus are dominantly built up of Saalian morainic deposits (till and glaciofluvial sand). This older relief was only partially reshaped by the relatively thin ice sheet of the Weichselian glaciation.

3.2 Weichselian glacial

During the maximum advance of the last Scandinavian ice sheet, the low-lying area was completely covered by the glacier. The maximum extent reached a few kilometres south of the basin along a line, marked by the Krausnick hills, the basin of Oderin and hills to the south of Teupitz. The glacier ploughed up a contour line that attracted the subglacial drainage. Thus, the Dahme channel was cut into the underlying sediments of Weichselian and Saalian age. Later the channel became filled with gyttja and peat (Fig. 5). Subglacial channels are a common feature in the young moraine area to the south of Berlin. A few kilometres to the west, there is the neighbouring channel of the Teupitz lakes.

Further south, in the Oderin basin, the subglacial Dahme channel reached the Baruth ice-marginal valley. There, the meltwater was discharged via a glacier gate to the subaerial valley. However, traces of subglacial drainage are not well-preserved in the Oderin basin.

With the beginning of the melting of the ice sheet, the subglacial channels could have been filled in by meltwater sed-

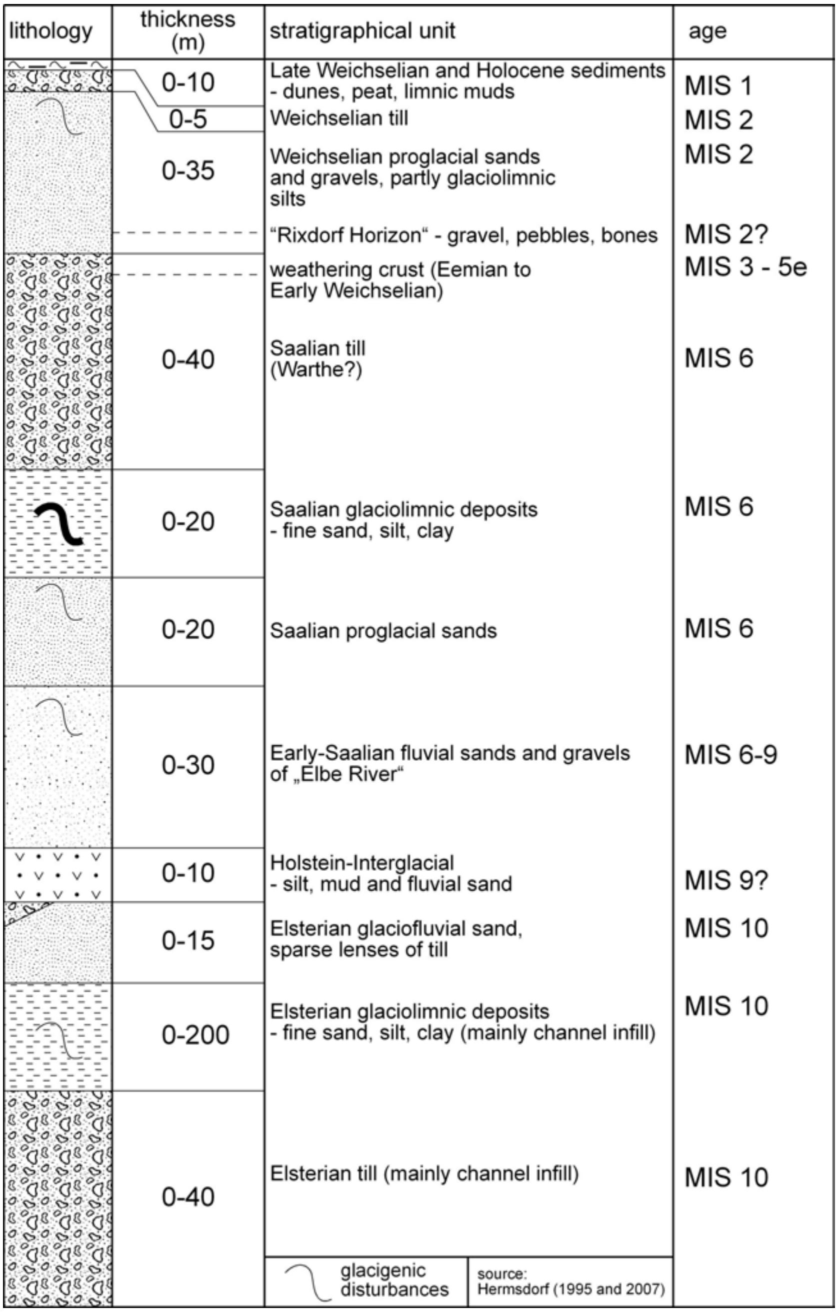

Figure 2. Composite profile of Quaternary sediments to the south and south-east of Berlin.

iments and blocks of dead ice. The contiguous body of ice disintegrated into individual blocks that gradually melted in the following. The Dahme channel, as well as the channel of the Teupitz lakes, was deactivated and sealed with dead ice.

3.3 Weichselian glaciofluvial phase

With the ongoing progress of the melting of the ice sheet, the low-lying area of Märkisch Buchholz was formed by subaerial meltwater streams. Subsequently, the Baruth ice-marginal valley fell dry. The meltwater stream had several outlets to flow from the basin of Märkisch Buchholz first to the west and later to the north (Fig. 4). During the subsequent phases, different terrace levels were formed at between 45 and 37 m a.s.l. The edges of the surrounding morainic plateaus were incised by the meltwaters.

The dead ice that sealed the Dahme channel as well as the channel of the Teupitz lakes was covered by the sediment load of the meltwater and thus preserved. Moreover, some blocks of dead ice were also preserved outside the chan-

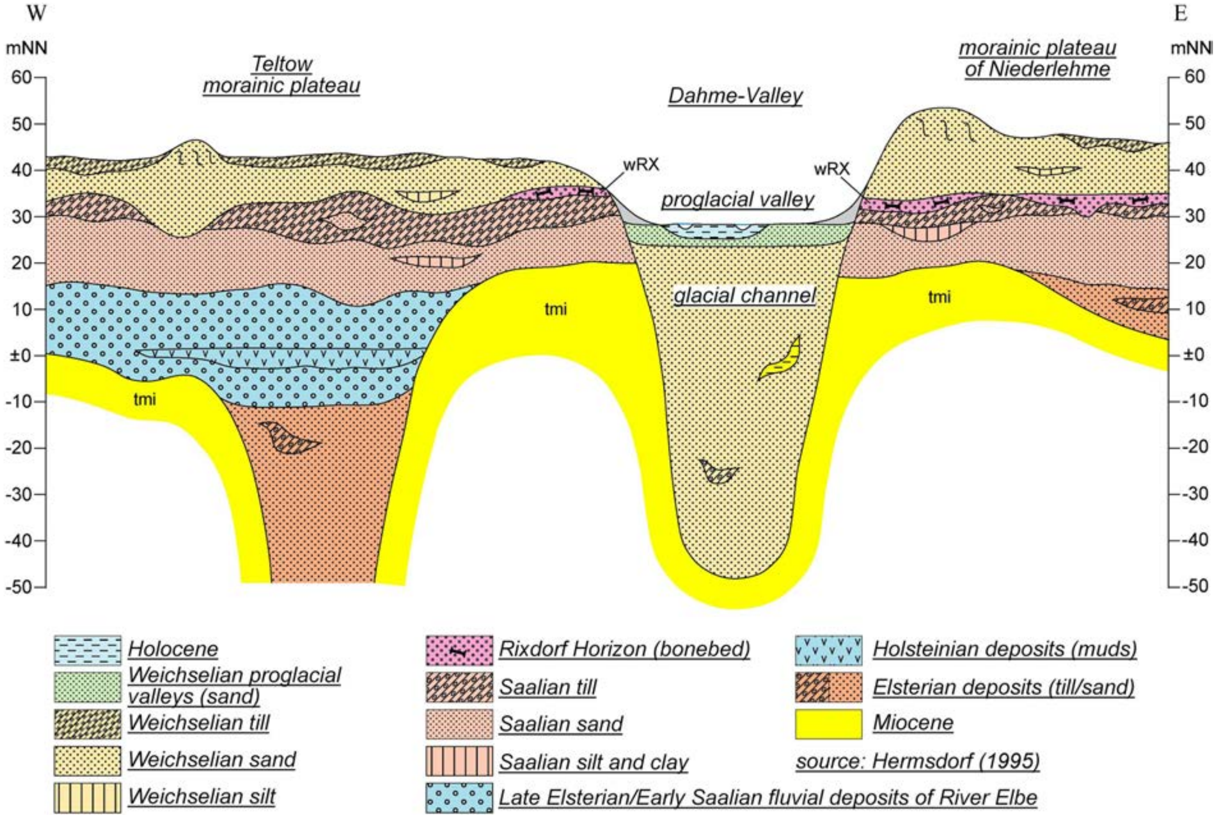

Figure 3. Geological scheme of Quaternary deposits close to the sandpit of Niederlehme.

nels. In the post-glaciofluvial phase, this conserved dead ice, which was a few metres thick only, thawed out to form shallow basins, regionally known as *Luche*.

The melting of the Weichselian ice sheet stopped to the north of Berlin during the Frankfurt phase. This was accompanied by the formation of the Berlin ice-marginal valley. As a result, the main outflow of the meltwater, which had previously flown through the Baruth ice-marginal valley and the basin of Märkisch Buchholz, was increasingly rerouted into the Berlin valley.

3.4 The periglacial and late glacial phase

After the meltwater flow had dried up, the basin of Märkisch Buchholz appeared as a low-elevation area with very low relief energy. It was completely covered by glaciofluvial sands. However, the area remained exposed to periglacial processes for several thousand years. Under the influence of westerly winds, large fields of dunes were formed, especially in the eastern part of the basin (Fig. 4). In addition to irregularly shaped dunes, parabolic dunes were formed. Some of the elongated dunes crossed the Dahme channel, which at that time was still sealed with dead ice.

In periglacial times, a precursor of the river Dahme (called the "Palaeo-Dahme") left the Baruth ice-marginal valley and flowed through the Oderin basin to the north. It hit the basin of Märkisch Buchholz from the south. At this time, the dead-ice infill of the Dahme channel gradually began to thaw. The river entered the resulting shallow depression and followed its course into the basin of Märkisch Buchholz. At Klein Hammer, the Palaeo-Dahme was dammed in front of a dune ridge that was blown onto the channel. At the so-called "Brennesselwiese", an overflow to the lowest terrace level of the meltwater streamway exists (Fig. 6). On this terrace level the river Palaeo-Dahme flowed to the north-west. Within this process, the Stintgraben lowland was cut into the surface of the basin of Märkisch Buchholz. A system of meandering palaeochannels was formed. Some of the mentioned *Luche* basins were fluvially reshaped by the river as well. Close to Klein Köris, the river Palaeo-Dahme flowed into the basin of the Klein Köriser See, which is part of the channel of the Teupitz lakes. To the north, the river used the channel to reach the Berlin ice-marginal valley.

This drainage path lasted until the dead ice that sealed the channel had thawed. The dune ridge near Klein Hammer sagged to such an extent that the river could break through. In consequence, the Stintgraben lowland fell dry.

While no exact dating is available from the palaeochannels of Stintgraben, in the south-eastern part of Berlin (Köpenick) comparable palaeochannels of the river Dahme could be dated to Allerød times (Grünert, 2002).

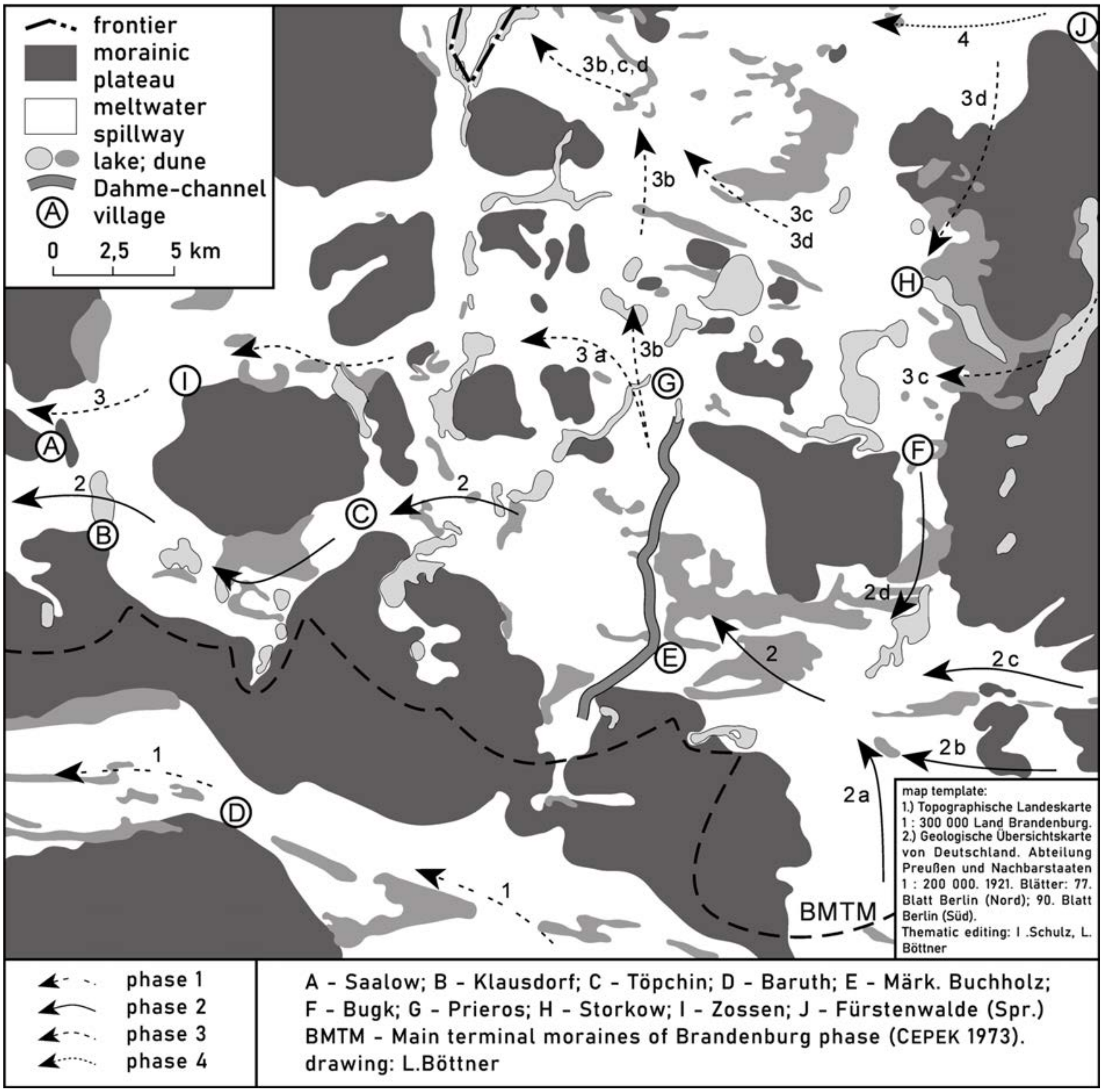

Figure 4. The system of meltwater streamways between the Baruth ice-marginal valley (Phase 1 in the south) and the Berlin ice-marginal valley in the north (Phase 4 in the north). Dunes as well as the Dahme channel have been drawn in.

3.5 The late glacial and Holocene phase

Following the beginning of the Bølling–Allerød phase, the last dead ice, preserved in the channels, largely thawed away. The climate warming at the beginning of the late glacial interstadial resulted in gradual reforestation, which was accompanied by a decrease in aeolian processes. In contrast to the deep channels, most of the shallow basins were dry during the Early Holocene. Due to the rise in the groundwater table at the transition from the Boreal to the Atlantic most of the basins became wet and peat growth was initiated. Muds and gyttja accumulated in the lake basins of the Dahme channel until peat growth commenced there. On the shores of the lakes of the Dahme channel, flint artefacts have been found, indicating the presence of Neo- and Mesolithic people in the early Atlantic period.

In historical times, the landscape of the basin of Märkisch Buchholz underwent a comprehensive transformation through increasing anthropogenic influence. Extensive clearing has transformed pine and oak forests into pasture and arable land. Pine forests were planted on dunes and sandy sites far from the groundwater table. The operation of the mill Hermsdorfer Mühle certainly led to a locally limited increase in the groundwater level. On the other hand, a large number of the above-mentioned *Luche* basins, wet-

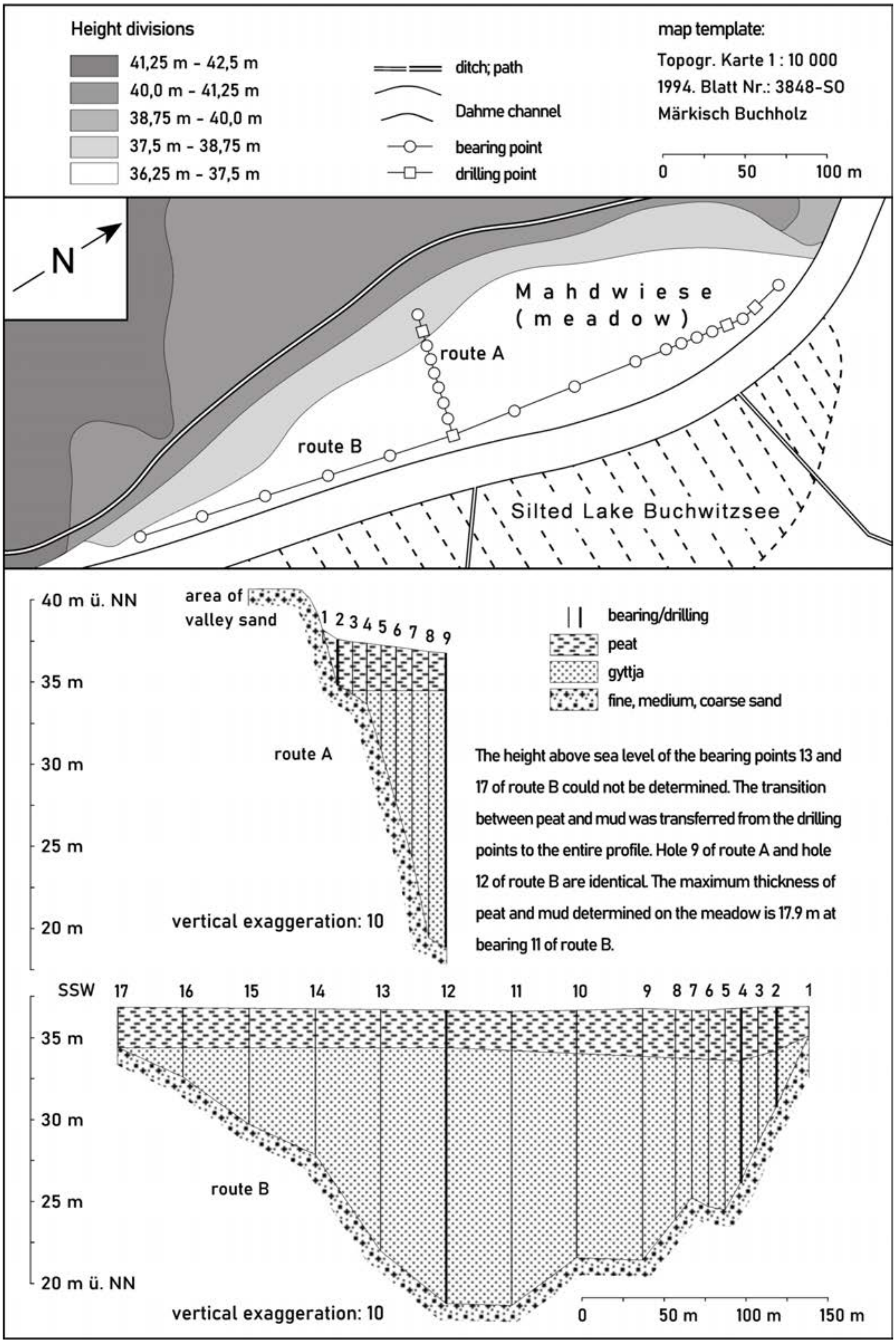

Figure 5. Geological profiles through the silted lake Buchwitzsee. It is situated in the southern part of the Dahme channel.

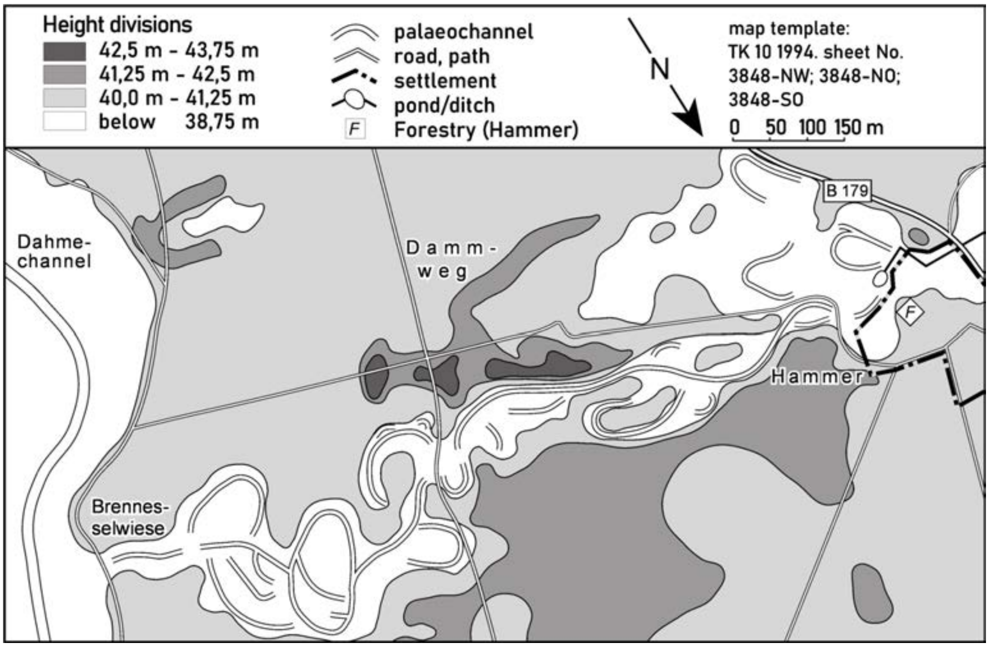

Figure 6. The system of late glacial meandering palaeochannels at the forester’s lodge Hammer.

lands inside the Dahme channel, damp sandy sites and the entire lower Stintgraben lowland were drained by means of ditches (Stintgraben, Laufgraben, Grenzgraben) in order to open them up to agricultural use. The construction of the artificial channel “Dahme-Umflutkanal” (to prevent floodwaters) completely straightened the river Dahme. These measures have largely ended peat growth and partially destroyed existing peat sites.

In forestry, efforts to overcome the long-running monoculture have been evident in recent years with the establishment of young pine–oak and pine–beech woodland plantations. However, the nature conservation measures planned by the environmental authorities so far have not been sufficient to preserve the wet landscapes of the sandy basin of Märkisch Buchholz.

4 Stop three: the southern margin of the (last) northern glaciation – morphology and land use history of the Krausnick hills

Reaching up to 144 m a.s.l., the Krausnick hills are by far the highest morainic plateau in the young moraine area to the south and south-east of Berlin. They form a remarkable contrast to the flat landscape of the Spreewald area.

The hills in their current shape are interpreted as being formed by several ice advances. While the main formation of the hills as an elevated area can be dated back to the Saalian Ice Age, the current surface and the near-surface sediments were mainly formed during the ice advance of the last Scandinavian ice sheet (SIS). Thus, older sediments can only be found in former clay pits on the northern slopes of the hills.

The Krausnick hills are crossed by the terminal moraines of the Brandenburg ice stage. This is in contrast to the Oderin basin further west and the Spreewald area to the east, where no terminal moraines formed. The Krausnick hills have very well developed moraine ridges. They appear to be superimposed on the older moraine complex.

The pre-existent elevated area acted like a pillar on the glacier of the last SIS. Even though it was completely covered by the youngest ice, it slowed down the expansion of the glacier further south. In contrast to this, the ice could advance further south in the adjoining low-elevation area of Unterspreewald. Therefore, the direction of the ice advance in the southern part of the Krausnick hills was from the east to south-east rather than from the north (Fig. 7). This unusual direction can be demonstrated by the course of the glacial channels in the western part of the Unterspreewald area. There, the channels are directed approximately from east to west. This led to an intriguing situation: there are two ridges of terminal moraines running east to west across the Krausnick hills. While the northern ridge was formed by the typical southward-advancing glaciers, the southern ridge was formed by glaciers advancing from the east to south-east. Between the two ridges there is a narrow, elongated outwash plain indicating a glacier mouth directly on top of the Krausnick hills. Further to the west, the narrow plain changes into a wide outwash plain called the “Brand”. In addition to the above-mentioned glacier mouth the Brand was fed by meltwaters from two other mouth areas. Both areas are characterised by their undulating surface and a wealth of kettle holes.

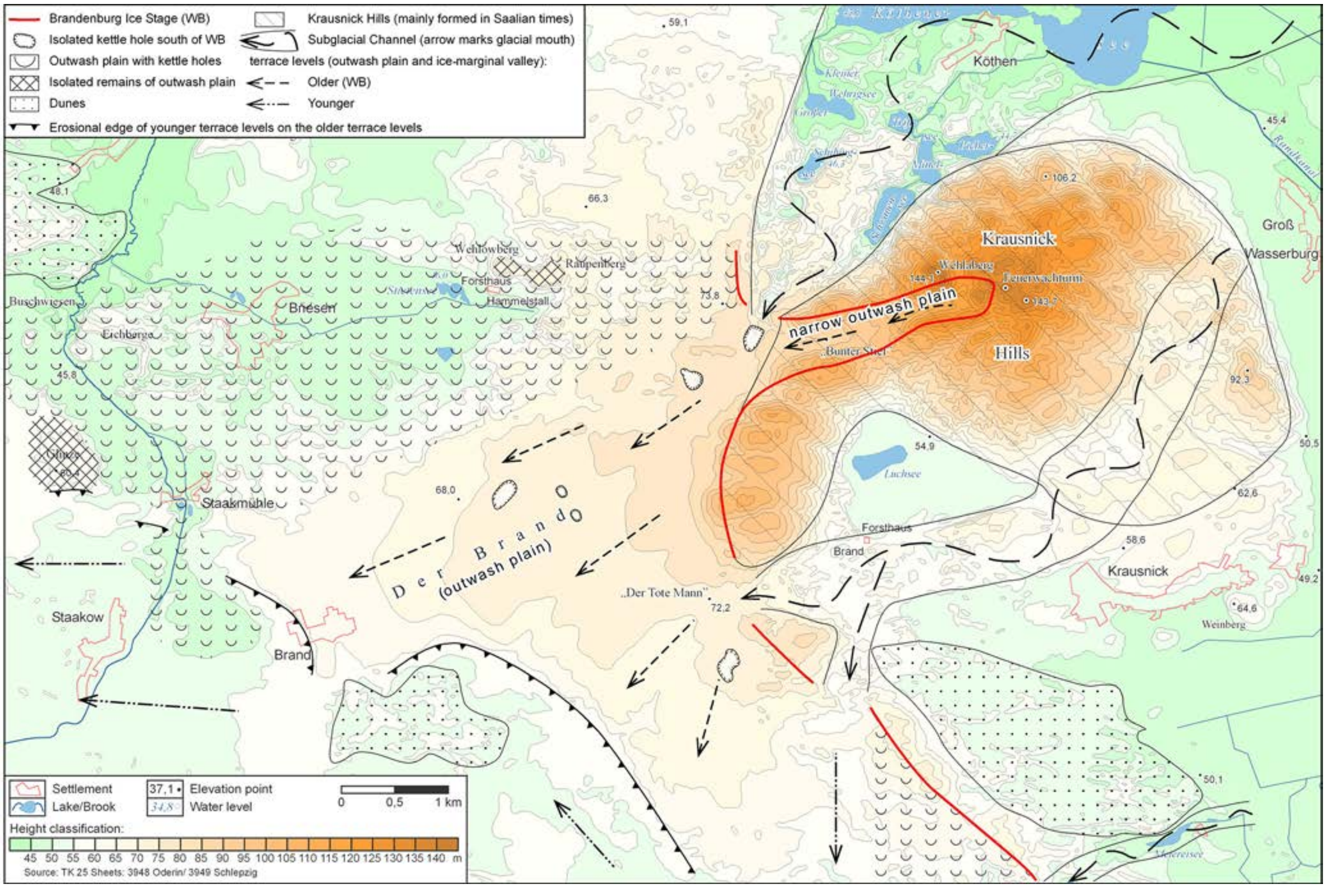

Figure 7. Morphological scheme of the Krausnick hills and their surroundings.

In earlier times, the Krausnick hills were mainly used as pasture woodland. As witnesses of this use, some large and old oaks are still present.

Data availability. Underlying data can be found at https://doi.org/10.18452/14585 (Juschus, 2001). A list of the raw data for the fieldwork can be found in the Appendix of the file Juschus.pdf.

Author contributions. OJ wrote Sect. 1 as a literature review. Section 2 was written by OJ. For this section, the results of the joint fieldwork of OJ and MB were used. In addition, existing literature was evaluated. Section 3 was written mainly by LB, with additions by OJ. The results of LB's fieldwork were used for this section. Section 4 was written by OJ. For this section, the results of the joint fieldwork of OJ and MB were used. Figures 1, 2, 3, and 7 were made by OJ, and Figs. 4, 5, and 6 were made by LB.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Ice dynamics in the SW sector of the Scandinavian Ice Sheet (SIS) – a fresh perspective from the classical area of the Weichselian glaciation in northern Brandenburg

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Abstract: The glacial landscape of northern Brandenburg, especially the Eberswalde–Chorin area, is one of the most important study areas of Quaternary research in northern Germany, not only with respect to its research history, but especially with regard to new mapping, sedimentological logging, and dating results using up-to-date methodologies. These new results have added an important puzzle-piece contributing to the development of a new concept of ice dynamics in the SW sector of the Scandinavian Ice Sheet (SIS) during Marine Isotope Stage 2 (MIS 2). After an introduction to the glacial geomorphology of the area, key sites visited during the field trip are explained, and the recent results are introduced and discussed.

1 Introduction

The glacial landscape of north-eastern Germany has been one of the type areas in Quaternary research ever since the first steps towards a consistent glacial theory were taken in the second half of the 19th century (summarised in Lüthgens and Böse, 2011). Notwithstanding this important role in research history, the area has experienced a boost in scientific relevance throughout the last decade(s), now being one of the areas providing the most comprehensive geochronological record for the last glacial cycle in the south-western sector of the Scandinavian Ice Sheet (SIS; summarised in Lüthgens et al., 2020). An important point that makes the area particularly suitable for such research is the fact that especially in Brandenburg, the ice-marginal positions of the Weichselian glaciation are not only developed well north of the maximum extent of the penultimate glaciation (Fig. 1) but were in fact also developed well apart from each other (Fig. 2), allowing for a relatively straightforward assignment of landforms and sediments to specific ice advances. The aim of this field trip was to demonstrate the exceptionally well-preserved and textbook-like geomorphology and sedimentology of the glacial series (*Glaziale Serie*) of the Pomeranian (W_2) ice-marginal position in the Eberswalde–Chorin area, contrasting it with the challenging geomorphological and sedimentological record of the area assigned to the "vanishing" Frankfurt (W_{1F}) ice-marginal position. Over the last years, several geomorphological and geochronological studies applying up-to-date methodology (Lüthgens et al., 2011, 2010a, b; Lüthgens and Böse, 2011, 2012; Hardt et al., 2015, 2016, 2021; Hardt and Böse, 2016; Heine et al., 2009; Brauer et al., 2005; Rinterknecht et al., 2006, 2012) in that broader

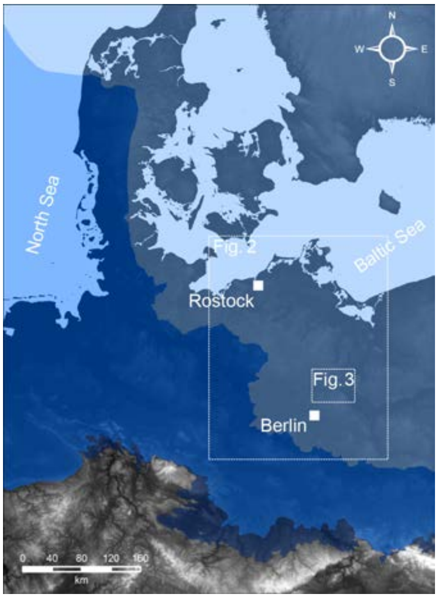

Figure 1. Maximum extents of the Elsterian (dark blue), Saalian (blue), and Weichselian (light blue) glaciations (from south to north) in the south-western sector of the SIS (figure modified from Lüthgens and Böse, 2011; data from Ehlers and Gibbard, 2004).

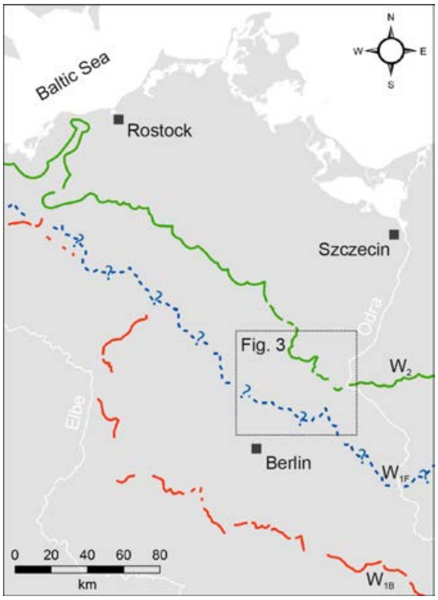

Figure 2. Ice-marginal positions in north-eastern Germany and north-western Poland according to the (traditional) morphostratigraphic system (based on Liedtke, 1981). The existence of an W_{1F} ice-marginal position has been challenged based on results from recent research (presented during the field trip) and is only included here as a dotted line with question marks for spatial reference (figure modified from Lüthgens and Böse, 2011).

area have generated important results, which have significantly contributed to a new understanding of the ice dynamics and glacial landscape development in north-eastern Germany (Lüthgens et al., 2020). Consequently, the route of the field trip (Fig. 3) started on a drumlin-shaped elevation, the "Kleiner Rummelsberg", north of the W_2 ice-marginal position, leading to the terminal moraines of the global Last Glacial Maximum (G-LGM) at the Ihlowberge and Sperlingsherberge sites, to the area of the LGM proglacial outwash plains in an ice-proximal setting at the Althüttendorf gravel pit, and to the ice-proximal site of the Macherslust site. Leaving the area of the G-LGM, the route then leads to the Albertshof and Ladeburg sites (Fig. 3), where the ice dynamics and landscape development are associated with the ice advance to the local LGM (L-LGM), which reached its maximum position well south of the field trip area at the Brandenburg ice-marginal position (W_{1B}), and its subsequent decay is discussed. The aim of the field trip was to demonstrate that, rooted in a long tradition of research, applying up-to-date methodology and integrating results from geomorphology, sedimentology, and geochronology (Lüthgens et al., 2020) have changed the view on and initiated a fresh and fruitful discussion about the dynamics of the south-western sector of the SIS in the last glacial cycle.

2 Kleiner Rummelsberg (geomorphological overview)

Situated in the glacial basin of an ice lobe that formed the terminal moraines framing the area of the Parstein lake ("Parsteiner See"), the 82 m high elevation of the Kleiner Rummelsberg (52.912955° N, 13.981974° E) provides an excellent viewpoint to gain an overview of the typical glacial geomorphology of the area (Fig. 4). To the west, south, and east, the view is framed by the G-LGM terminal moraines of the Pomeranian stage ("Parsteiner Bogen"), while the direct surroundings of the Kleiner Rummelsberg itself are dominated by multiple lakes, which developed in the depression of the glacial basin (*Gletscherzungenbecken* in terms of the classical glacial series; Fig. 5). Towards the north, the view is open and shows the transition of the lake-dominated basin to the hummocky areas of the till plain associated with the G-LGM ice advance. Apart from the Kleiner Rummelsberg itself, multiple hills are present within the glacial basin. The processes that formed these hills have been controversially discussed. Originally, they were interpreted to represent a local, recessional ice-marginal position, formed during the retreat of the ice front from the terminal moraine of the Parsteiner Bogen (Brose, 1978). However, some of the insular hills like the Kleiner Rummelsberg itself have an elongated, drumlin-like shape, which may likely indicate that these hills may represent older landforms, which have been overridden by the L-LGM advance of the Parstein ice lobe to the Pomeranian ice-marginal position.

3 Ihlowberge–Sperlingsherberge (terminal moraines of the Pomeranian stage)

Within the Brandenburg area, the terminal moraines of the Pomeranian ice-marginal position are not only very clearly geomorphologically expressed, they are also rather exceptional with respect to the high content of boulders within the sediment building the terminal moraines (*Blockpackung*). Lacking any alternative hard-rock resources, these boulder-rich sediments were discovered early on as a raw material source, spawning a quarry industry in the mid-18th century. The sites Ihlowberge (52.959169° N, 13.836481° E) and Sperlingsherberge (52.972477° N, 13.855360° E; Fig. 6) are both abandoned quarries from that time and today offer access to the sediments of the Pomeranian terminal moraines (Hultzsch, 1994), showing the rare *Blockpackungen* (Fig. 7). Both sites are also part of the "Geopark Eiszeitland am Oderrand" (roughly translating to geopark for the "ice age landscape adjacent to the Oder River"). Information with regard to the geopark can be accessed via the park's website https://www.geopark-eiszeitland.de/ (last access: 28 July 2022).

Boulders from the terminal moraine surface were among the first to be dated by means of surface exposure dating (SED) using cosmogenic nuclides (specifically ^{10}Be) in north-eastern Germany (Heine et al., 2009). Methodological advances in cosmogenic nuclide dating required a recalculation of these ages, which was conducted by Hardt and Böse (2016), resulting in ages around 18–20 ka, indicating the retreat of the ice front from its G-LGM position at that time.

4 Althüttendorf gravel pit (ice-proximal sandur sediments)

Figure 8 shows that the terminal moraines of the G-LGM create an interlobate area framed by the terminal moraines of the "Joachimsthaler Bogen", which functioned as a main meltwater drainage, resulting in the deposition of the sediments forming the Althüttendorf outwash plain ("Althüttendorfer Sander", named by the nearby village). This outwash plain is part of the complex pattern of intercalated glaciofluvial sedimentary units south of the Pomeranian ice-marginal position (summarised in Lüthgens et al., 2011), analysed in detail by Krambach and Böse (2017). Figure 8 summarises the major routes of meltwater and related glaciofluvial outwash deposits in the area. While the main discharge from the Althüttendorf area was most likely routed south-west via the Werbellinsee depression, smaller fan-shaped outwash cones seam the southern margins of the Pomeranian terminal moraines. The fans form the Ragöse, Amtsweg, and Klosterbrücke sandurs and indicate restricted meltwater activity in the Eberswalde ice-marginal valley as opposed to previous interpretations by, for example, Liedtke (1956) or Börner (2007) at that time (Krambach and Böse, 2017). The meltwaters which where drained through the glaciofluvial gap in the area of the Chorin Monastery originated from a recessional ice margin north of the Pomeranian terminal moraines (like the Angermünde and Parstein subphases). The exact drainage and routing of these meltwaters is still under debate, but Krambach and Böse (2017) show that the Eberswalde ice-marginal valley did not drain significant amounts of meltwater during that time as well. This makes a rerouting of meltwater as proposed by, for example, Liedtke (1956) and Kozarski (1966) more likely and challenges the previously established model based on a glaciofluvial terrace system in the Eberswalde ice-marginal valley (summarised by Gärtner et al., 1995).

The sediments of the Althüttendorf outwash plain are accessible in one of the largest gravel pits in Brandenburg (52.961308° N, 13.867619° E; Fig. 6). Access to the pit is only possible with permission by the operating company and is otherwise strictly forbidden. Given its ice-proximal position, the Althüttendorf outwash sediments mainly consist of sands and gravel with a percentage of 20 %–25 % of coarse material > 2 mm (Hultzsch, 1994), but on the upper part of the ~ 16 m of exposed sediments, intercalated diamictons can be found. These can usually be separated into a lower diamicton containing large quantities of clasts of boulder size, which is often overlain by a matrix-supported diamicton containing a moderate number of stones and smaller blocks. Both diamictons may be interpreted as debris flow deposits (Lüthgens et al., 2011) originating from the ice margin by destabilisation of sediments deposited on the ice front during phases of short re-advances (Fig. 9). Similar deposits have been described by Pisarska-Jamroży (2006) in Chelm, close to the Pomeranian ice-marginal position, in western Poland. In addition, pockets of fine sediments (mainly silts and fine sands) were deposited in puddles and depressions caused by either the unsettled landscape surface induced by debris flow activity or the thawing of buried dead ice (Lüthgens et al., 2011). Depending on the outcrop conditions, these fines often show intense cryoturbation features (Fig. 9). In many places, these fines are again overlain by a matrix-supported diamicton, containing only significantly smaller clasts than the lower ones, which can be interpreted as a periglacial cover sediment (Lüthgens et al., 2011).

The outwash sediments of the Althüttendorf sandur and the Klosterbrücke outwash cone (about 10 km south-east of the Althüttendorf site), both being of the same morphostratigraphical relative age within the glaciofluvial drainage system of the region, were dated by means of optically stimulated luminescence (OSL) by Lüthgens et al. (2011). Mean ages based on multiple samples of 20.1 ± 1.6 ka for Althüttendorf (initial phase of W_2 sandur deposition) and of

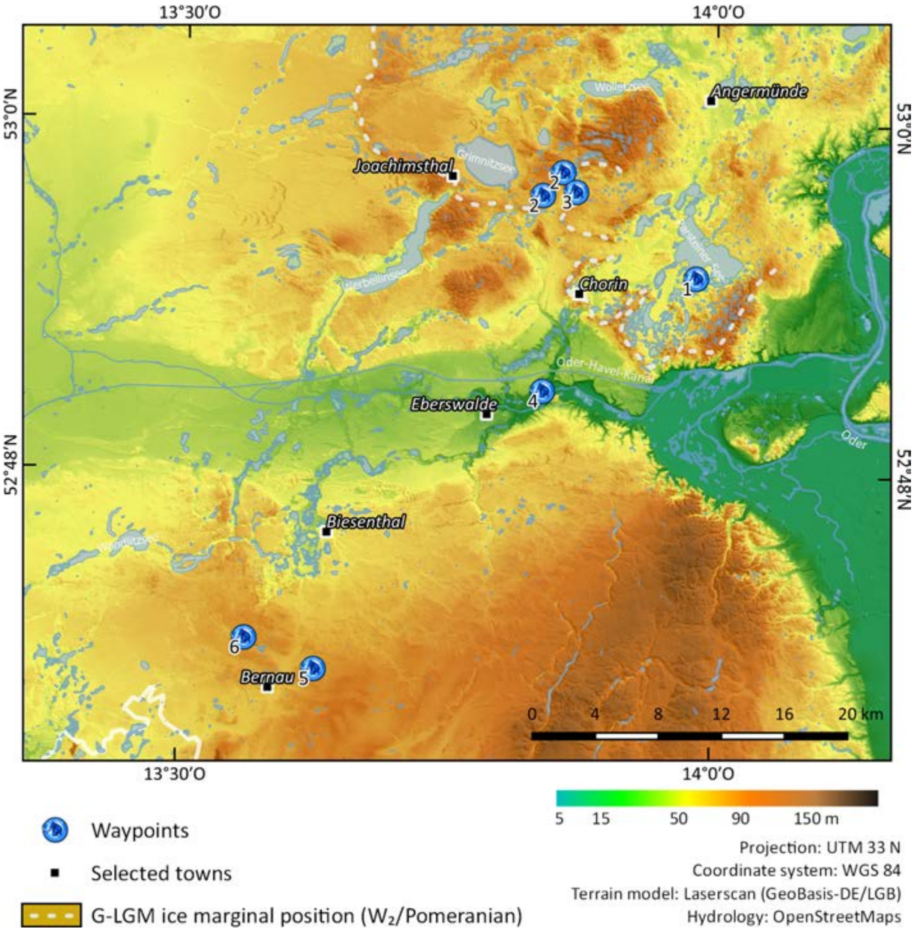

Figure 3. Overview map of the route of the field trip with waypoints to be visited. (1) Kleiner Rummelsberg (geomorphological overview), (2) Ihlowberge–Sperlingsherberge (terminal moraines of the Pomeranian stage), (3) Althüttendorf gravel pit (ice-proximal sandur sediments), (4) Macherslust clay pit (banded silts and clays), (5) Albertshof gravel pit (the vanishing of an ice-marginal position – part 1), (6) Ladeburg gravel pit (the vanishing of an ice-marginal position – part 2). Hydrology: © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

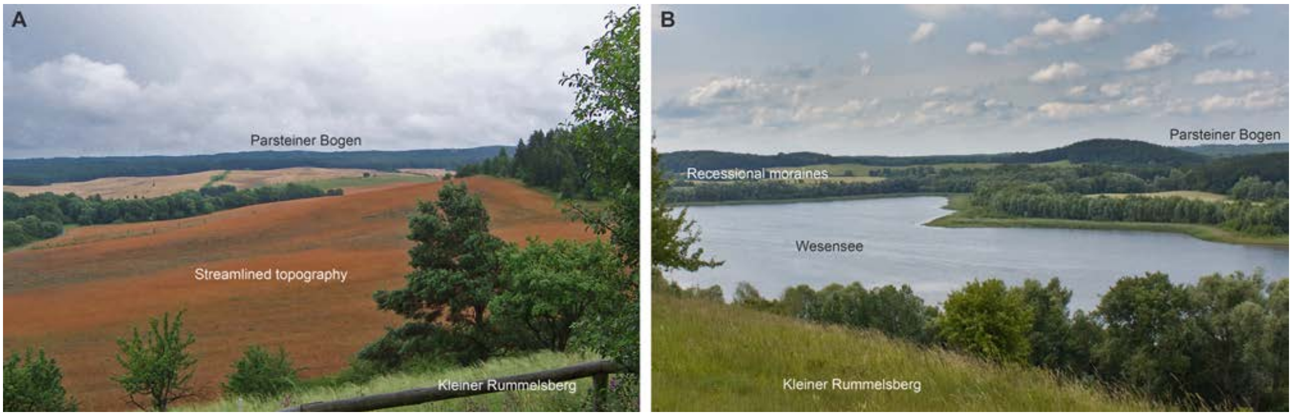

Figure 4. Views from the top of Kleiner Rummelsberg: **(a)** view to the south-east, showing the W_2 terminal moraines of the Parsteiner Bogen in the background and the streamlined, drumlin-like topography in the foreground (photo by Christopher Lüthgens, 2007). **(b)** View to the south–south-west, showing again the W_2 terminal moraines in the background and recessional moraines bordering the shore of Wesensee (photo: Christopher Lüthgens, 2007; modified from Lüthgens and Böse, 2011).

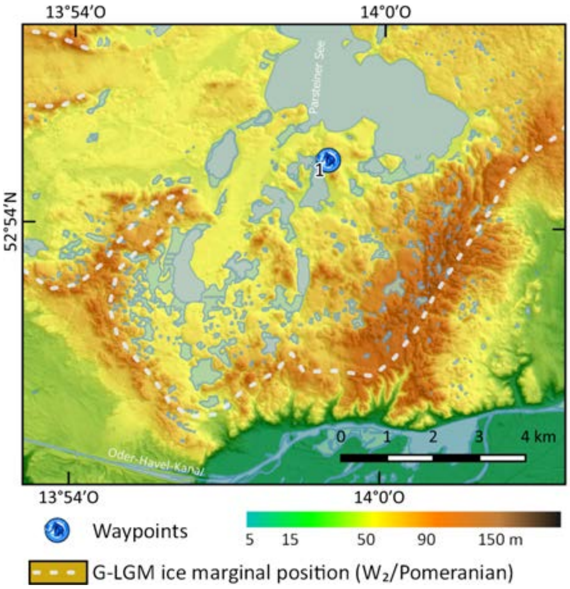

Figure 5. DEM of the *Gletscherzungenbecken* surrounded by the G-LGM terminal moraines of the Parsteiner Bogen (W_2). Waypoint 1: Kleiner Rummelsberg. Map projection: UTM 33° N; coordinate system: WGS 84; terrain model: Laserscan (GeoBasis-DE/LGB, 2020); hydrology: © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

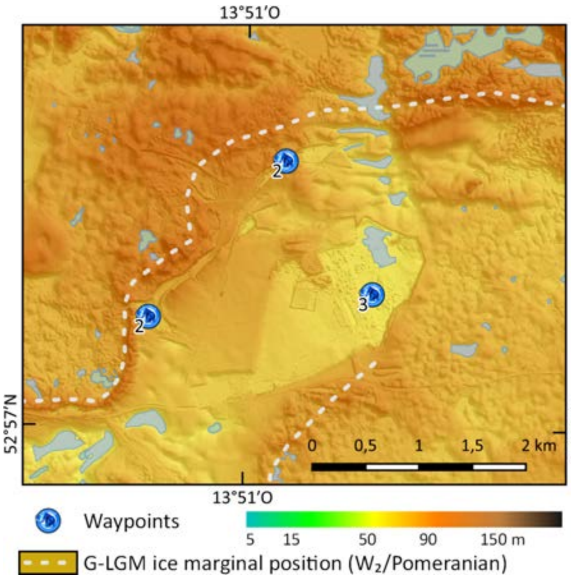

Figure 6. DEM of the Althüttendorf area. (2) *Blockpackungen* of Ihlowberge (north) and Sperlingsherberge (south), (3) Althüttendorf gravel pit. Map projection: UTM 33° N; coordinate system: WGS 84; terrain model: Laserscan (GeoBasis-DE/LGB, 2020); hydrology: © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

19.4 ± 2.4 ka for the Klosterbrücke (final phase of W_2 sandur deposition) correlate nicely with the G-LGM.

5 Macherslust clay pit (banded silts and clays)

In an abandoned clay pit (52.847582° N, 13.838394° E) in the Torún–Eberswalde ice-marginal valley near Macherslust (Fig. 10), north-east of the town of Eberswalde, banded clays and silts are exposed, which were deposited in a depression most likely formed by melting dead ice below ground (Marcinek and Schulz, 1995; Fig. 11). The 1–25 cm thick laminated silt layers and 2–10 mm thick clay layers dip to the west–north-west at an angle of $\sim 10°$, which was interpreted as an effect of continued melting of dead ice after deposition of the sediment succession (Schirrmeister, 2004). Because of a subaquatic slide that must have happened before the sediments were consolidated, part of the exposed section is intensely deformed. Although Pisarska-Jamroży (2013) uses the term "megavarves" to describe the sediments at Macherslust, the laminated sediments do not reflect annual layers (Schirrmeister, 2004). The succession of banded silts and clays is frequently intercalated with layers of fine sand, which is a clear sign that the glacio-lacustrine conditions were repeatedly interrupted by phases of streaming water conditions. According to Schirrmeister (2004) and Pisarska-Jamroży (2013), this indicates an influence of glacial meltwater originating from a distant ice margin. Lüthgens et al. (2011) dated the deposition of one of these sand layers to 14.7±1.0 ka. However, based on the available age constraints Krambach and Böse (2017) argue that the phase of deglaciation in the context of the Pomeranian ice advance (following a process-based interpretation of SED and OSL ages) occurred significantly earlier, and the deposits of Macherslust only reflect a phase of melting of buried dead ice and ongoing periglacial processes.

6 Albertshof gravel pit (the vanishing of an ice-marginal position – part 1)

The route of the field trip now leaves the textbook glacial landscape of the Pomeranian ice-marginal position to the south (Fig. 1) and enters the landscape of the Barnim Plateau – an area traditionally ascribed to the Frankfurt ice-marginal position (W_{1F}). However, recent research based on high-resolution analysis of a lidar DEM and subsequent fieldwork has shown that the area is actually lacking any geomorphological features like terminal-moraine-like landforms that could represent an ice-marginal position (Hardt et al., 2015). Instead, a succession of arcuate till ridges could be identified, with all ridges showing similar forms and dimensions, with a length varying between 1–1.5 km and a width of 10–15 km; they rise 6–10 m from their surrounding areas (Hardt et al., 2015; Fig. 12). The ridges are also identical with respect to their sedimentological composition, with the ridges all con-

Figure 7. Outcrop in the terminal moraines at the abandoned quarry of "Sperlingsherberge" showing the high content of blocks (*Blockpackung*). However, the characteristics of the proglacially deposited diamicton building the terminal moraines vary between matrix- and clast-supported segments and also include segments of glaciofluvial sediments (photo: Margot Böse, 2011).

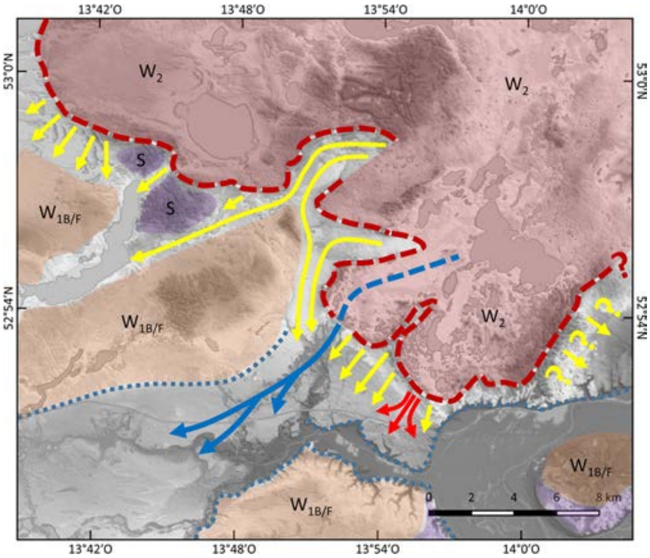

Figure 8. Simplified depiction of meltwater discharge in the field trip area (based on Fig. 2 of Lüthgens et al., 2011), incorporating the new results from Krambach and Böse (2017). Meltwater from the area of the Pomeranian ice-marginal position (shaded red area; terminal moraines indicated by the dashed red line) was mainly drained from the Althüttendorf area around higher terrain formed by previous Weichselian (orange shaded areas; $W_{1B/F}$) or even Saalian (purple shaded areas; S) ice advances to the south-west and south-east. Outwash deposition was otherwise mostly limited to fans in front of the terminal moraines (yellow arrows). Final outwash drainage and deposition of meltwater deposits associated with the Pomeranian ice-marginal position are documented in the outwash fan of "Klosterbrücke" (bright-red arrows). After the ice front had retreated to recessional stages further north, meltwater was channelled through the Chorin gap (blue arrows) to the meltwater channels (delimited by dashed blue lines) south of the Pomeranian ice-marginal position. Map projection: UTM 33° N; coordinate system: WGS 84; terrain model: Laserscan (GeoBasis-DE/LGB, 2020).

sisting of till deposited on top of glaciofluvial sands and meltwater deposits deposited in between the ridges (Hardt et al., 2015).

In the Albertshof gravel pit near Bernau (Fig. 12), the sediments of one of these ridges are exposed (52.687559° N, 13.627338° E). While the northern part of the pit consists of stratified sands and gravels (Fig. 13) topped by a nonstratified unit (*Geschiebedecksand*), the sediments of the ridge itself are accessible in the southern part of the pit. Here, a massive diamicton is exposed, containing 10 %–17 % of clay and silt and reaching a thickness of up to ~ 4 m (Fig. 14). Stratified sands underlie this diamicton. The sedimentary pattern exposed here (glaciofluvial sands below the till ridges with meltwater sediment infills between the ridges) was also confirmed by means of electrical resistivity tomography (ERT) measurements in the vicinity of the gravel pit. These measurements covered a distance of about 700 m and allowed for interpretation of the sediments up to a depth of about 16 m below the landscape surface (Hardt et al., 2015).

7 Ladeburg gravel pit (the vanishing of an ice-marginal position – part 2)

The Ladeburg gravel pit is located about 5 km west of the previously described Albertshof gravel pit (Fig. 12) and is also situated on the fringe of one of the aforementioned lobate ridge structures (52.704494° N, 13.562466° E). This very ridge had been interpreted as representing the Frankfurt ice-marginal position W_{1F} by previous authors (e.g. Hermsdorf et al., 1998). As described in Hardt et al. (2016), the sediment succession exposed in the upper part of the Ladeburg gravel pit, as well as ERT measurements in the vicinity of the pit, corroborates the findings from the Albertshof area with regard to the structural architecture of the arcuate ridges.

The excavation depth in the Ladeburg pit of up to almost 20 m below the landscape surface (Fig. 15) allows excellent access to a succession of sediments, which, at least in the upper part, had previously been ascribed to the W_{1F} stage (Franz et al., 1970). The outcrop is dominated by layers of sands and gravel, which are intercalated by two mas-

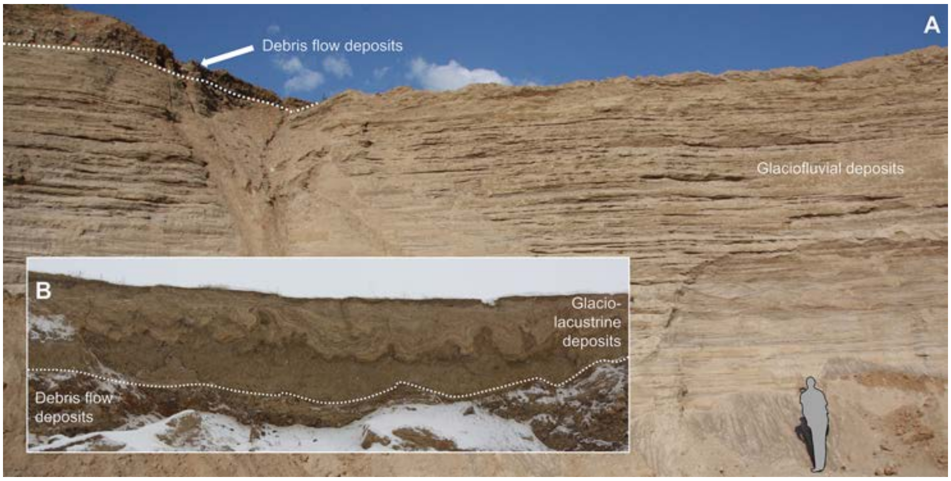

Figure 9. Typical sediments of the Althüttendorf gravel pit: **(a)** glaciofluvial sands and gravels covered in part by diamictons deposited by debris flow events (photo: Christopher Lüthgens, 2016). **(b)** Glacio-lacustrine fines deposited on top of the irregular relief of the debris flow deposits showing post-depositional cryoturbation structures (photo: Christopher Lüthgens, 2009).

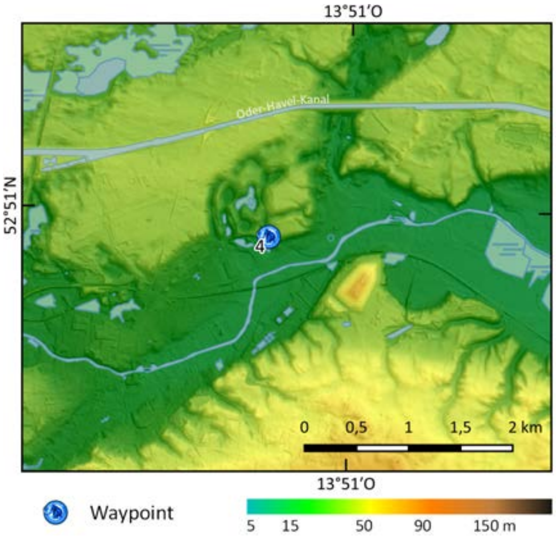

Figure 10. DEM of the Macherslust area in the southern part of the Torún–Eberswalde ice-marginal valley. Waypoint 4: abandoned clay pit. Map projection: UTM 33° N; coordinate system: WGS 84; terrain model: Laserscan (GeoBasis-DE/LGB, 2020); hydrology: © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

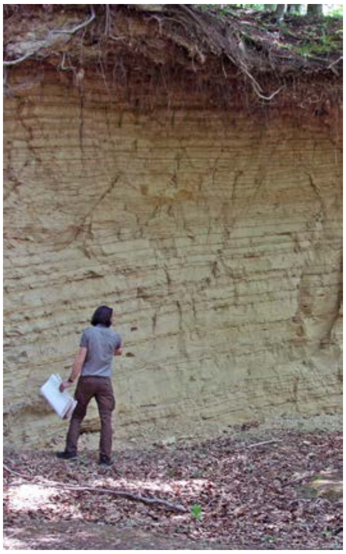

Figure 11. Banded clays and silts exposed in the abandoned pit near Macherslust showing the dip of the sediments to the west–northwest and some deformation structures towards the top of the outcrop (photo: Christopher Lüthgens, 2016).

sive matrix-supported diamictons. The upper diamicton has a thickness of about 1 m and occurs about 4 m below the surface. Towards the north of the pit, this diamicton thickens and transitions into and forms the ridge structure as described above. The lower diamicton has a thickness of about 2 m and occurs about 8 m below the surface. Directly below this diamicton, cryoturbation features within sand and gravel layers may indicate a former landscape surface. Hardt et al. (2016) provide a chronology for this sediment succession using OSL dating of the glaciofluvial sands. The lower diamicton is framed by luminescence ages between a minimum age of > 148.6 ± 10.4 ka (underlying sands below the cryoturbation structures) and an age of 34.3 ± 4.4 ka (overlying sands). The exact chronostratigraphic position of the lower till therefore remains unclear, but fine-gravel analyses conducted by Gärtner (1993) yielded a Saalian spectrum for the till. The upper diamicton, however, is framed by luminescence ages between 33.7 ± 4.7 ka (underlying sands) and 25.1±3.7 ka (overlying sands), providing an excellent age es-

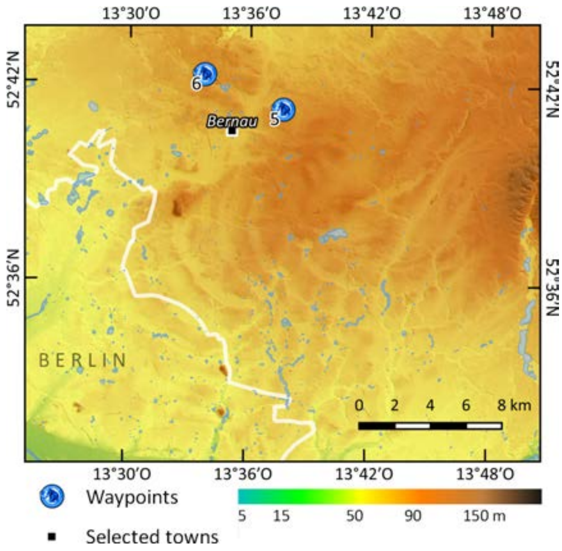

Figure 12. DEM of the arcuate till ridges on the Barnim Plateau. This area was previously ascribed to the Frankfurt ice-marginal position (W_{1F}). Please note that the till ridges are also visible within the Berlin city limits (white line). (5) Albertshof gravel pit, (6) Ladeburg gravel pit. Map projection: UTM 33° N; coordinate system: WGS 84; terrain model: Laserscan (GeoBasis-DE/LGB, 2020); hydrology: © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

Figure 13. Cross-bedded glaciofluvial sands and fine gravels exposed in the Albertshof gravel pit. Length of the shovel for scale approximately 1 m (photo: Christopher Lüthgens, 2016).

timate for the formation of the ridge, which most likely also applies to the formation of the other ridges in the Barnim area (Hardt et al., 2016). Taking all available geochronological data from the broader area into account (Lüthgens et al., 2010a, b, 2011, 2020; Lüthgens, 2011; Hardt et al., 2016), the formation of the ridges can be ascribed to the phase of ice decay and ice front retreat from the L-LGM position, the Brandenburg or W_{1B} stage. Because there are no indications of a stable ice margin in the area, the ridges representing the W_{1B} recessional phase replace the W_{1F} ice-marginal position in the Barnim area.

Figure 14. Glacial till exposed in the Albertshof gravel pit. This till forms one of the arcuate ridges (compare Fig. 12) typical for the Barnim area (photo: Christopher Lüthgens, 2016).

8 Summary

These new results from the sites visited during this field trip clearly show the importance of a process-based interpretation of numerical ages and call for a time-based reconstruction of ice sheet extents, as opposed to the traditional morphostratigraphical approach, which inevitably results in time-transgressive reconstructions and models. Only by using a time-based reconstruction can the available numerical ages (summarised for the Brandenburg area in Fig. 16) serve as vital tools for the reconstruction of ice sheet dynamics. Following this approach, Lüthgens et al. (2020) recently proposed a new conceptual model for the reconstruction of ice dynamics in the south-western sector of the SIS in MIS 2. The new insights gained in the area visited during this field trip have significantly contributed to opening new doors for the interpretation of the dynamics in the south-western sector of the SIS with multiple new and fascinating scenarios now within the realm of possibility, as proposed by Lüthgens et al. (2020).

Figure 15. Panoramic view from the northern edge of the Ladeburg gravel pit to the south, showing the size of the excavation and the outcrop wall that was investigated by Hardt et al. (2016). Panorama composed of 10 photos taken by Christopher Lüthgens (2016).

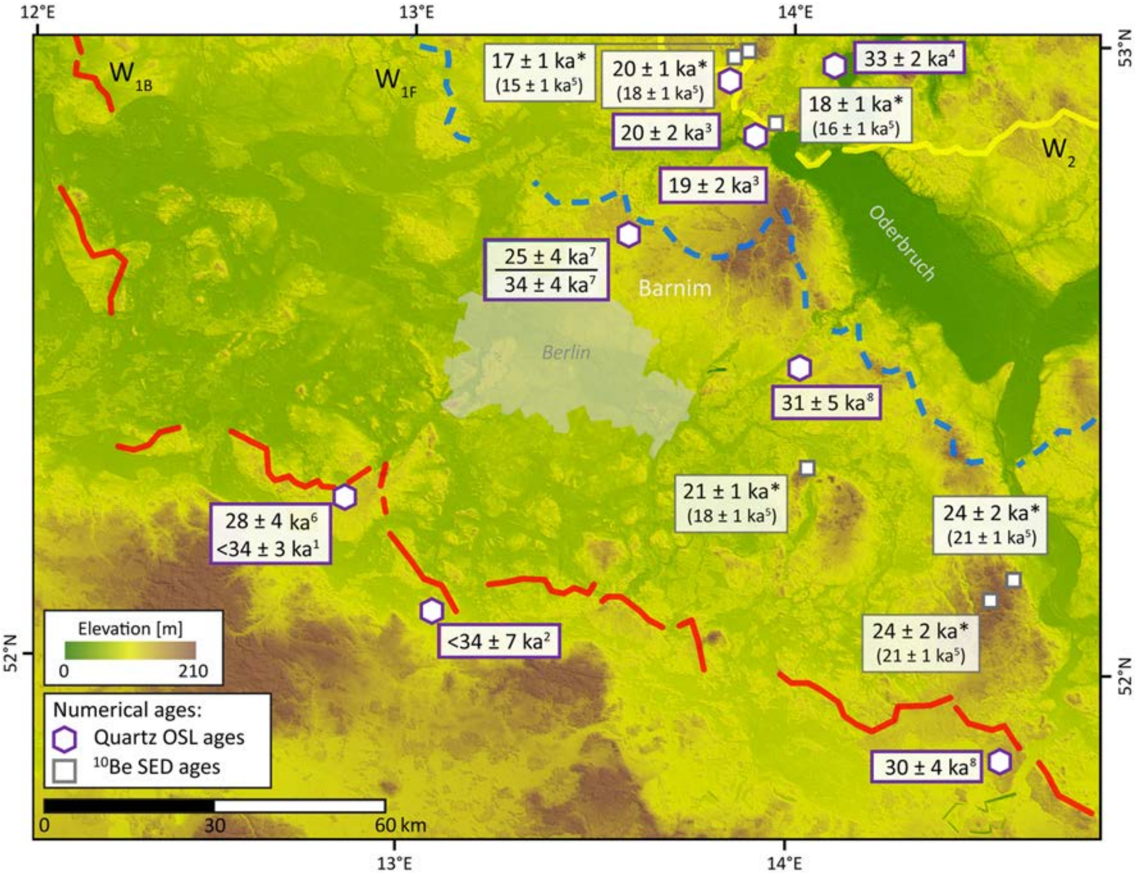

Figure 16. Summary of OSL and SED ages: [1] Lüthgens et al. (2010a), [2] Lüthgens et al. (2010b), [3] Lüthgens et al. (2011), [4] Brauer et al. (2005), [5] SED ages (asterisks indicate the recalculated ages from Hardt and Böse, 2016, using CRONUS online (Balco et al., 2008) and the alternative calibration dataset by Heyman 2014; original ages provided in brackets), [6] Lüthgens (2011), [7] Hardt et al. (2016), [8] Lüthgens et al. (2020). Base map derived from hillshaded SRTM data. Figure modified from Hardt (2017).

Data availability. All cited datasets can be accessed publicly via the referenced original publications. In addition, Table 1 in Lüthgens et al. (2020) provides a compilation of most of the cited datasets.

Author contributions. CL and JH have planned the field trip route. CL and JH conducted the literature research and composed the maps. CL prepared the original draft, which was reviewed and edited by JH.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Lakes and trees as climate and environment archives: the TERENO Northeastern German Lowland Observatory

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Abstract: Robust reconstruction of past climate and environmental change based on proxy data obtained from natural archives requires an in-depth understanding of the processes and mechanisms that form and determine these proxies. Here we present comprehensive long-term monitoring projects for seasonally laminated (varved) lake sediments and tree rings in the northern German lowlands. The two monitoring sites are located in the nature park Nossentiner/Schwinzer Heide (Tiefer See) and in the Müritz National Park (tree rings) and are an integral part of the Helmholtz TERrestrial ENvironmental Observatories (TERENO) infrastructure initiative. Both sites are located in the close vicinity of moraine deposits of the main ice advance of the Pomeranian phase of the Weichselian glaciation. This field guide provides an introduction to the local morphologies and landscapes as well as details of the monitoring concepts and some selected results.

1 Introduction

Climate and environmental changes in the past are reconstructed from a wide range of chemical, physical and biological proxy data obtained from different types of geoarchives. For a robust interpretation of these proxy data it is crucial to understand how climate and environmental signals translate into proxy data. A common approach for an advanced reading of proxy data is to monitor processes by observing and measuring lacustrine sedimentation and growth rates of trees in combination with meteorological parameters at high temporal resolution. This enables us to identify which weather parameters are well reflected and which are less well reflected in sediment records or tree rings. It can be assumed that climate information is different in different geoarchives, and, therefore, the largest gain is achieved by combining several archive types. Here, we focus on annually laminated lake sediments and tree rings as two seasonally resolving archives. A critical factor for monitoring approaches is their duration, which often is limited due to the high cost and human resources required. However, given the pronounced interannual variability and the need to observe effects especially of rare extreme years and events, more information and crucial process understanding will be gained the longer an observation can be maintained. The monitoring sites presented here have run for a decade as an integrated part of the TERrestrial ENvironmental Observatories (TERENO) initiative.

1.1 TERENO

Global change has triggered a number of environmental changes, such as alterations in climate, land productivity, water resources, atmospheric chemistry and ecological systems. Finding solutions to the impact of global change is one of the most important challenges of the 21st century. Therefore, the Helmholtz Association has set up four terrestrial observatories, forming the focus regions of the TERENO network. TERENO stands for TERrestrial ENvironmental Observatories (Zacharias et al., 2011). The observatories were selected to be representative of Germany and other central European regions with the highest vulnerability with respect to climate change effects (Zebisch et al., 2005).

The overall aim of TERENO is to monitor climate change impacts on the terrestrial system in Germany for at least 15 years. Terrestrial systems in TERENO comprise the subsurface environment, the land surface including the biosphere, the lower atmosphere and the anthroposphere. These systems are organized along a hierarchy of spatial scales ranging from the local scale to the regional scale. Furthermore, temporal scales ranging from directly observable monitoring periods to longer periods of up to millennial timescales derived from bio- and geoarchives are considered. With regard to the latter, TERENO concentrates on precisely dated and annually to sub-seasonally resolved synchronized long-term data from lake sediments and tree rings. The overarching goal is to develop process studies based on comprehensive monitoring of bio- and geoarchives to gain a robust understanding of the climate and environmental signal transfers into these archives (Zacharias et al., 2011).

1.2 Monitoring aims

In addition to monitoring the regional impacts of recent climate change, the specific goal of the Northeast German Lowland Observatory (TERENO-NE) is to extend climate and environmental time series several millennia back in time by seasonally resolving proxy data from lake sediments (varves) and tree rings. Such time series are essential to evaluate ongoing change with respect to natural variability. This approach requires in-depth understanding of geochemical, biological and sedimentological (in the case of lakes) proxies for an advanced and robust interpretation. Our approach, therefore, includes the integration of analyses of sediment profile and tree-ring series with observations of changes and their causal mechanisms through high-resolution monitoring. In doing so, weather and climate parameters as well as site-specific responses that control the formation of the proxies can be deciphered (Heinrich et al., 2018).

1.3 Site selection

In an ideal world, the lake and tree-ring observatories should be at exactly the same location, but due to the specific requirements for each observatory, we had to select two different sites locations within the northeastern German lowlands. After detailed site surveys, we selected Tiefer See in the nature park Nossentiner/Schwinzer Heide for lake monitoring because in this lake presently annual laminations (varves) are formed which are required for seasonal reconstructions from sediment records. The tree-ring observatory was installed in a southeastern direction from Tiefer See in the catchment of Hinnensee in the Müritz National Park because at this location we found a forest with old trees and various tree species growing along a pronounced altitudinal gradient with respect to the shore of Hinnensee. This gradient is required to fully assess the various responses of different trees and tree species growing under different groundwater conditions. Since the distance between the lake and tree monitoring sites is less than ca. 55 km, the climatic conditions are considered largely identical. The same holds for the geological and geomorphological situation because both sites are located in the close vicinity of the main W2 ice advance during the Pomeranian stage of the last glaciation (Fig. 1).

1.4 Present-day climate

The climate is warm–temperate at the transition from oceanic to continental conditions (Scharnweber et al., 2011). The average monthly temperatures vary between 0 °C in January to 17–18 °C in July with maxima of up to 30 °C and minima down to −5 °C. The mean annual precipitation amounts to 560–570 mm with seasonal averages ranging between ca. 40 mm during winter months and ca. 60 mm in summer months (Heinrich et al., 2019).

2 The lake observatory Tiefer See

Tiefer See has been selected for long-term monitoring mainly because it presently forms annual laminations, i.e. calcite varves. Another advantage of this lake is the lack of any infrastructure on the lake shore like roads and buildings. On the one hand, this minimizes direct human impact on the lake, but, on the other hand, it complicates the logistics for maintaining the monitoring especially during wet seasons when access to the lake is challenging.

Tiefer See is located at the eastern margin of the nature park Nossentiner/Schwinzer Heide at 53°35.5′ N, 12°31.8′ E and is part of the Klocksin lake chain, a subglacial gully system formed during the last glaciation. Abundant errat-

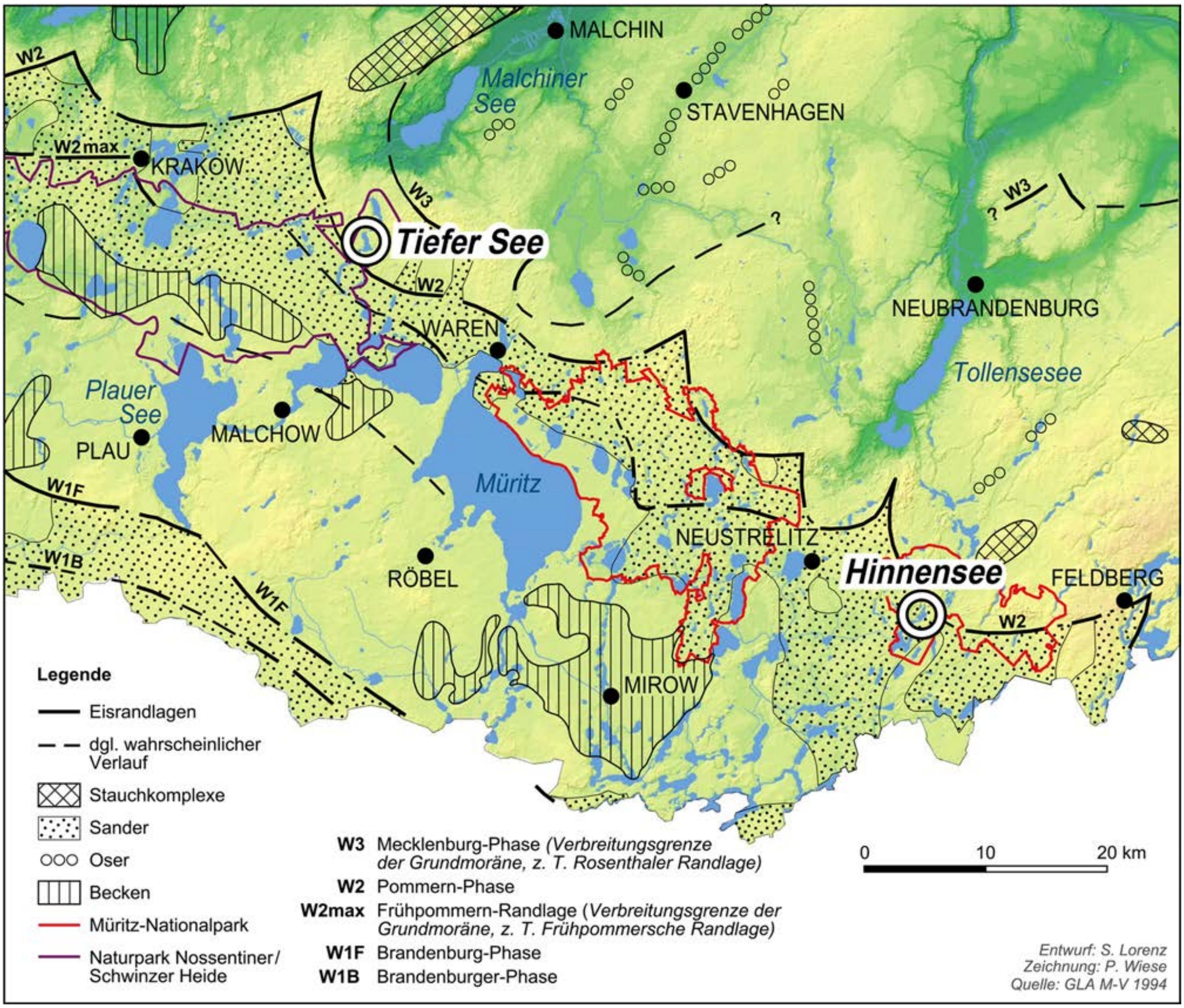

Figure 1. Location of observatories: Tiefer See (lake site; NW of Waren) and Hinnensee (tree site; SE of Neustrelitz). Both locations are close to the terminal moraine of the Pomeranian of the last glaciation (W2).

ics on the shoreline of the lake indicate its close proximity to the W2 terminal moraines of the Pomeranian phase. The Pomeranian ice advance has been radiocarbon dated at ∼ 16.5 ka cal BP (e.g. Uścinowicz, 1999) and at about 20 ka by optically stimulated luminescence (OSL) dating (Lüthgens et al., 2011) and recalibrated exposure dating (Hardt and Böse, 2018). The catchment is mainly formed by glacial tills except a small shallow part in the SE which consists of old lake deposits that were accumulated when there was a higher lake level, presumably during the late glacial period.

The Klocksin lake chain begins north of the former ice margin and extends for ca. 16 km from NNE to SSW. It includes the four lakes Flacher See (64.4 m a.s.l.), Tiefer See, Hofsee (62.7 m a.s.l.) and Bergsee (62.6 m a.s.l.). Today, Tiefer See is connected to Hofsee in the south, while the connection to Flacher See in the north has been channelized in a tunnel after construction of a railway dam between the two lakes in the late 19th century. The surface area of Tiefer See is ca. 0.75 km^2, and the catchment area is about 5.5 km^2. With a maximum depth of 62–63 m Tiefer See is the deepest lake of the lake chain. It has no major inflow and outflow. The present-day lake water is mesotrophic, and the circulation mode is either mono- or dimictic, depending on the formation of a winter ice cover (Kienel et al., 2013). On the shoreline of the lake a narrow band of predominantly large oak trees forms a kind of shelter separating the lake from intensive agriculture with crop fields in the catchment (Fig. 2).

Tiefer See is one of the few lakes in northern Germany that has formed varves for about 100 years. During other time intervals in the past, for example, the Medieval Warm Period, varves have also formed, which, however, differ in structure and composition from the modern varves (Dräger

Figure 2. View of Tiefer See (53°35.5′ N, 12°31.8′ E) from the north. White circle shows position of the monitoring station on a platform anchored at the deepest part of the lake basin.

et al., 2017), The alternation between varved and non-varved sediment sections throughout the Holocene depicts the high sensitivity of this lake with respect to varve formation and preservation. This characteristic makes the lake an ideal site to investigate processes that cause the presence of varves in order to ultimately use these varves as proxies for climate and environment changes in the past. So far, reports on climatic and human factors influencing sedimentation (e.g. Kienel et al., 2013, 2017; Dräger et al., 2017; Theuerkauf et al., 2015; Nantke et al., 2021) have emphasized the difficulty in distinguishing between both factors from analyses of the sediment record. This is exemplarily demonstrated in a detailed reconstruction of Holocene lake level changes proving that lake levels are not solely controlled by climate but by a complex interaction between climate, vegetation and human impact (Theuerkauf et al., 2022). The latter can be either indirect through modification of vegetation cover, direct through drainage or damming measures, or both. Interestingly, decadal to centennial lake level fluctuations are superimposed by a generally increasing trend from the early Holocene until today, which probably is related to changes in the Earth's orbit resulting in increasing winter insolation and decreasing summer insolation and thus reduced seasonal amplitudes. Presumably, these insolation changes caused a modification of atmospheric circulation with an increase in moist air masses from the Atlantic reaching northeastern Germany. Comparing long- and short-term lake level fluctuations shows that the total amplitude of > 9 m by far exceeds observed variations of ca. 1 m in the last 2 decades.

2.1 The sediment record

Seven long and overlapping sediment core sequences have been obtained from the deepest part of the lake basin with the GFZ UWITEC piston coring device during three expeditions in 2011, 2013 and 2019. A composite profile from cores taken in 2011 and 2013 (TSK11-A, TSK11-B and TSK11-C and TSK13-E and TSK13-F) has been established based on robust macroscopic and microscopic correlation layers (Fig. 3; Dräger et al., 2017). Two minor gaps due to coring issues below 750 cm have been bridged with two additional core sequences from 2019 (TSK19-H, TSK19-K). This final and continuous composite profile is about 1200 cm long and reaches glacial sands and gravel at the base, which were deposited after melting of dead ice. Lacustrine sedimentation commenced in the late Allerød or early Younger Dryas. The sharp onset of organic sediments at 1138 cm sediment depth coincides with the pollen-defined onset of the Holocene (Martin Theuerkauf, personal communication, 2021). Holocene sediments mainly consist of three components, authigenic and terrestrial organics, biogenically formed calcite, and diatom frustules. Due to the lack of a major inflow, detrital components are rare and mostly consist of scattered silt-sized quartz and carbonate grains. Modern varve formation commenced about a century ago and is favoured by anthropogenic eutrophication (Kienel et al., 2013). A prominent characteristic of the Holocene sediment profile is alternation of homogeneous and varved sediment intervals with various varve micro-facies types described by Dräger et al. (2017) (Fig. 3).

In addition to the long sediment profile from the deepest part of the lake basin, numerous short cores from the sediment surface of down to 150 cm depth have been obtained from all parts of the lake basin (Fig. 4). Their records provide detailed insight into the spatial propagation of the sediments. For most parts of the basin, sediment variations are small and only the onset of varve preservation varies with water depth (Dräger et al., 2019). In shallower water depths, varves start several decades later than in deeper water. This is due to the gradual expansion of anoxic conditions of the bottom waters. For example, at a water depth of 35 m varves have occurred only since 1980 CE; they began forming 60 years later than at 62 m water depth. At two locations in the northern and southwestern part of the basin, sediments appear very differently. Organic Holocene sediments are no more than 60 cm thick and deposited directly on top of glacial till. In the sediment seismic image these locations are clearly visible (Fig. 4) as black spots which indicate small morainic remnants within the subglacial valley that forms the lake basin.

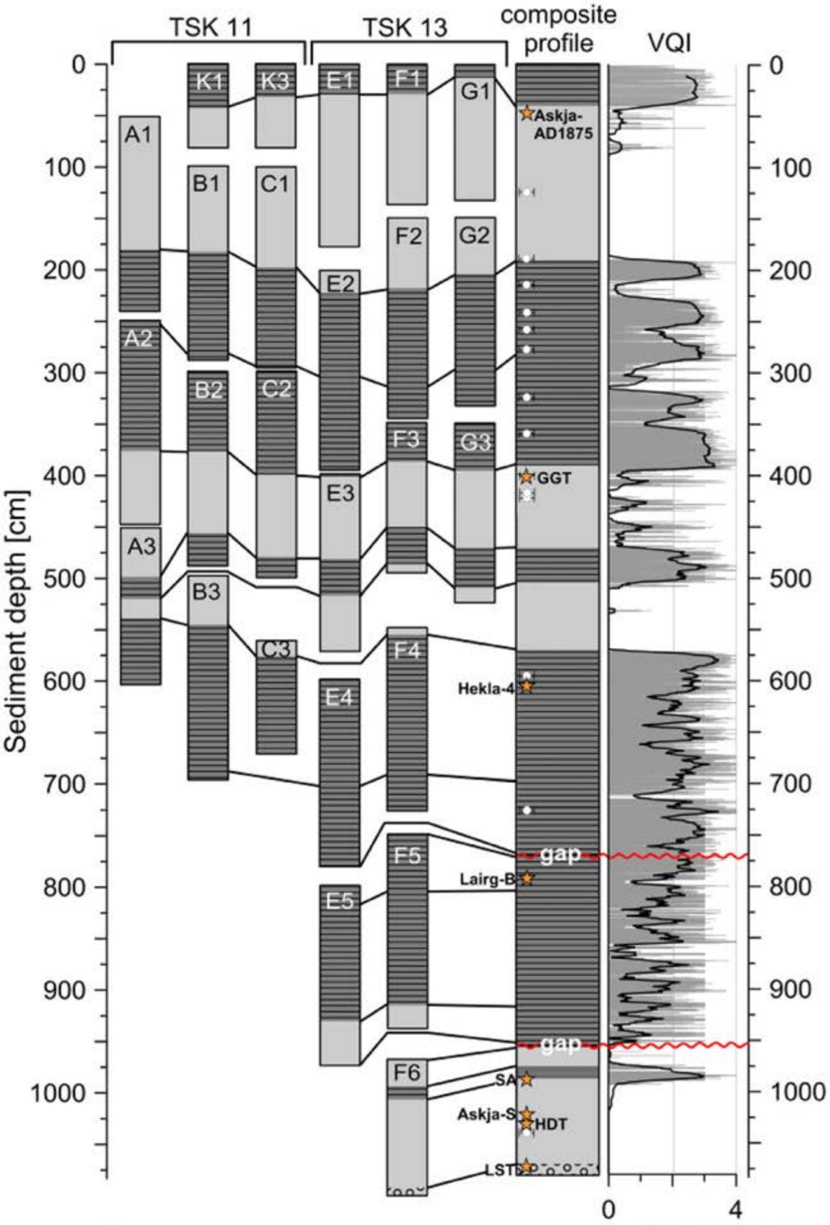

Figure 3. Composite profile from 2011 and 2013 cores comprising the last ca. 6000 years (from Dräger et al., 2017). Indicated are varved and homogeneous sediment intervals and the degree of varve preservation (varve quality index (VQI): high values reflect well-preserved varves). Cryptotephra horizons are indicated. LST: Laacher See tephra; HDT: Hässeldalen tephra; SA: Saksunarvatn ash; GGT: Glen Garry tephra.

2.2 Chronology

The age model for the sediment profile is based on varve counting, radiocarbon dating and tephrochronology. Varve counting is restricted to annually laminated intervals and provides robust information about sedimentation rates that are used to support dating of non-varved intervals. In addition, varve counting provides the link to the present since varve formation has occurred until today. Besides varve counting 28 radiocarbon dates from well-defined organic macroremains are included in the age determination of the chronology. Of these dates, 14 are published in the age model covering the last 6000 years (Fig. 5; Dräger et al., 2017), while the other 14 radiocarbon dates in the age range between 6000 and 11 600 a cal BP are still unpublished.

Another seven anchor points for the chronology are provided by tephrochronology. Besides the 1–2 mm thick visible layer of the Saksunarvatn ash (10 210 ± 35 a cal BP), six crypto-tephra horizons have been identified that can

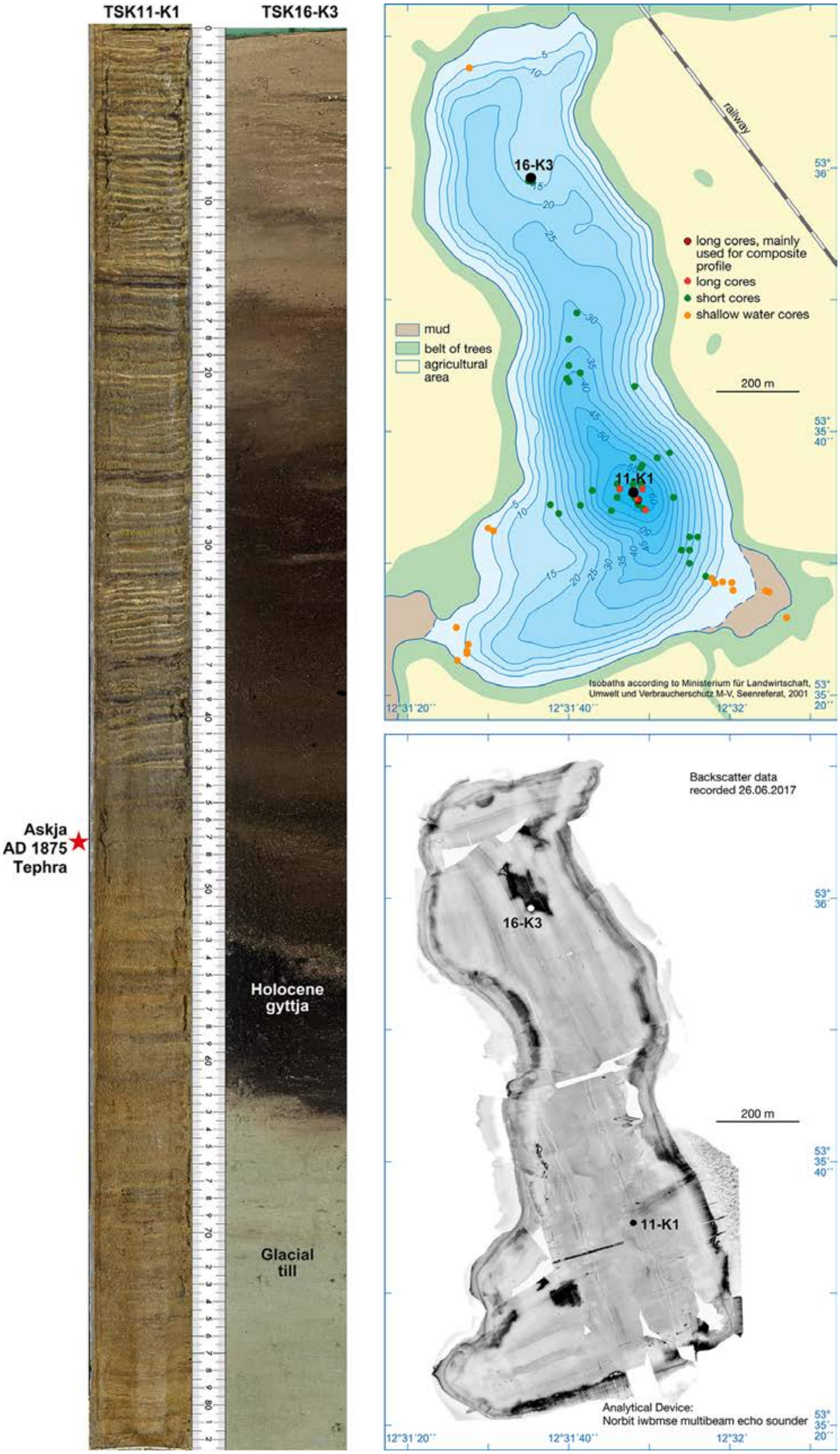

Figure 4. Bathymetric map with all core locations indicated. Black labels show the locations of the two cores shown to the left. Sediment seismic survey (lower right) carried out by Peter Feldens (in Theuerkauf et al., 2022).

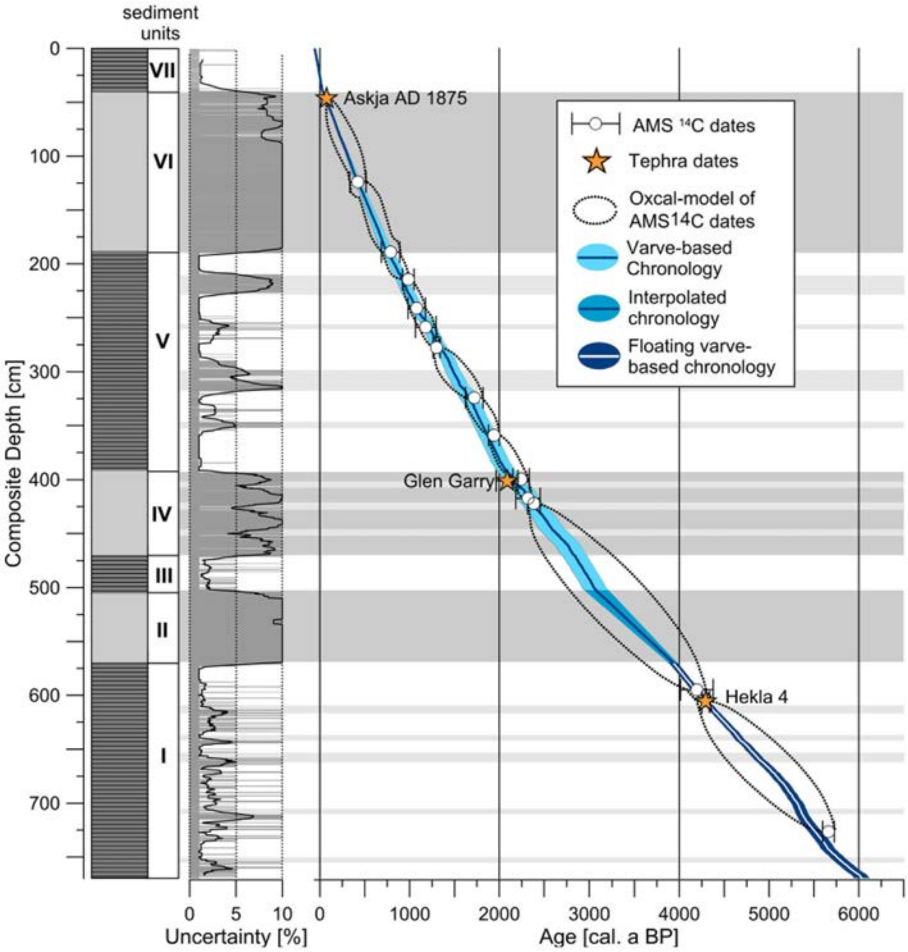

Figure 5. Age model for the Tiefer See sediment profile of the last 6000 years from Dräger et al. (2017). Coloured bars indicate intervals of poor varve preservation or non-varved intervals.

be assigned to known volcanic eruptions on Iceland: the early Holocene Hässeldalen and Askja-S tephras, the mid-Holocene Lairg-B (6683 ± 45 a cal BP) and Hekla-4 (4293 ± 43 a cal BP) tephras, the Glen Garry tephra (2088 ± 122 a cal BP), and the historical Askja-AD1875 tephra. The latter is an important time marker for the end of the Little Ice Age and appears 4 decades before the onset of varve formation. The Hässeldalen and Askja-S tephras occur in non-varved sediments and thus form essential time markers for a robust early Holocene dating. Besides their importance for dating the Tiefer See sediments, these tephra findings allow precise synchronization with other sediment records in the circum-Baltic region (Wulf et al., 2016) and beyond. Another emerging tool for synchronising sediment records is ^{10}Be analyses as a proxy for solar variability. In the sediments from Tiefer See three grand solar minima during the last 6000 years confirm the age model and provide time markers for synchronization (Czymzik et al., 2018).

Last but not least, an independent and precise determination of the onset of the Holocene has been achieved by pollen analyses (Martin Theuerkauf, personal communication, 2021).

2.3 Instrumental monitoring setup

Since 2012 permanent monitoring has been established in Tiefer See at the location from where the long Holocene sediment profile has been obtained (i.e the deepest part of the lake). At this position, weather and lake water parameters as well as sediment deposition at different water depths are continuously measured (Fig. 6). The monitoring setup includes an anchored platform with a weather station and profiler with a water probe measuring water and several lake water parameters down to a water depth of 55 m in 12 h intervals. Attached to this platform is a movable platform with a tripod used for water sampling at seven different water depths between 1 and 50 m, mainly for stable oxygen and deuterium isotopes in monthly intervals as well as for sampling surface cores once a year. A second pyramid-shaped platform with a profiler and water probe as backup is anchored at a short distance southwest of the main platform. Water measurements are carried out parallel to those with the water probe installed at the main platform. Weather and water monitoring is complemented by three different types of sediment traps collecting sediments at different time intervals and water depths: two four-cylinder traps at 12 m water depth below the thermocline and near the lake bottom at 50 m water depth integrate sedimentation over a month. A sequential sediment trap near the lake bottom collects sediments biweekly, and a two-cylinder trap installed as a backup nearby accumulates sediments in half-year intervals. Regular sediment analyses from all traps except the backup trap included measurements of total carbon, organic carbon and nitrogen as well as stable isotopes ($\delta^{13}C_{org}$, $\delta^{15}N$, $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$). The high-resolution data on biochemical calcite precipitation in the lake have been used, for example, to calibrate remote sensing data of regional calcite formation in northeastern German lakes (Heine et al., 2017). The monitoring concept is flexible and can be easily extended for limited time intervals in case it is needed for more specific research questions about, for example, processes of cyanobacteria deposition in the sediments (Nwosu et al., 2021a, b, c). More technical details about the monitoring devices installed can be found at https://www.gfz-potsdam.de/en/section/climate-dynamics-and-landscape-evolution/infrastructure/lake-sediment-monitoring (last access: 4 August 2022).

2.4 Modern varve formation

The primary goal of the lake monitoring is to decipher the processes of varve formation including seasonal effects and, in particular, those external forcing mechanisms that mainly control the depositional processes. Before starting the sediment monitoring at Tiefer See it was known that calcite varves have been and preserved for about a century (Kienel et al., 2013). Calcite varves are the common varve type in annually laminated lakes in formerly glaciated areas of the southern Baltic lowlands and are described as light–dark couplets with the light layer representing endogenic calcite formation in spring and summer (Tylmann et al., 2013). Calcite precipitation occurs in the epilimnion of the lake because, there, light conditions favour photosynthetic activity of phytoplankton (i.e. diatom blooms) which exploits CO_2 from the epilimnion, leading to carbonate saturation (e.g. Kelts and Hsü, 1978). This process is clearly reflected in the sedimentation processes in Tiefer See, starting with a distinct diatom bloom during spring warming in April and/or in presently rare cases of longer winter ice cover immediately after the ice break-up (Fig. 7; Kienel et al., 2017; Roeser et al., 2021a). As reported from other calcite varves, we also observe a gradation of calcite crystal sizes from large crystals in the initial phase of calcite formation. The transition between the diatom and calcite sublayers is not sharp, confirming the causal relation between algal growth and calcite formation. Comparing calcite amounts in sediment traps from the epilimnion and hypolimnion reveals that sometimes parts of the calcite formed in the epilimnion are dissolved during settling through the water column (Roeser et al., 2021a).

The majority of calcite is deposited in May and June although from July to September some calcite formation may continue. In October, sediment deposition shifts from almost pure calcite to a mixture of different components including diatom frustules (more epiphytic taxa than planktonic); patches of calcite; plant fragments; and, rarely, scattered silt-sized detrital mineral grains. These sediments predominantly originate from shallower parts of the lake basin and are re-suspended by wind and wave activity during autumn mixing of the water column. In most years of the monitoring period, no longer period of ice cover occurred so that sediment re-suspension continued during winter. In summary, three distinct phases of sedimentation processes can be allocated to seasonal changes in the lake (Fig. 8): (1) diatom bloom, (2) calcite formation and (3) re-suspension. These phases form discrete seasonal sublayers in the sediment record that can be clearly identified through micro-facies analyses. In contrast, the macroscopic image reveals only light–dark couplets because the re-suspension and diatom layer together appear as a dark sublayer. This has to be considered for interpreting varve thickness data because very different processes determine the individual sublayers. In particular, wind and wave activity play a more important role for sedimentation than has previously been assumed. Besides the regular recurrence of the three phases of sedimentation, we observe substantial year-to-year variability in the quantity of sediments formed in each season. This variability appears to be largely driven by the timing and strength of water circulation (e.g. spring mixing) and wind-driven wave activity. Consequently, wind conditions and strength of water stratification seem to constitute a more important factor for sedimentation rate than temperature and precipitation.

3 The tree-ring and hydrological observatory Hinnensee

The observatory Hinnensee (Fig. 9a), located in the Serrahn part (SE) of Müritz National Park, was selected for several reasons. The landscape around Hinnensee is mostly flat, but the northern shores are an exception to this, as they are formed by steep slopes with altitudinal differences of up to 50 m within short distances (Kaiser et al., 2014), resulting in dry/wet micro-site conditions distant from/near to the groundwater at the uphill/downhill locations. The hydrological setting of the groundwater-fed lake Hinnensee is relatively simple. Its lake level is governed solely by water intake from precipitation plus surface runoff from the surrounding slopes and groundwater, as well as water loss from evapotranspiration. The lake has a narrow ratio of lake vs. catchment area and therefore shows immediate and signifi-

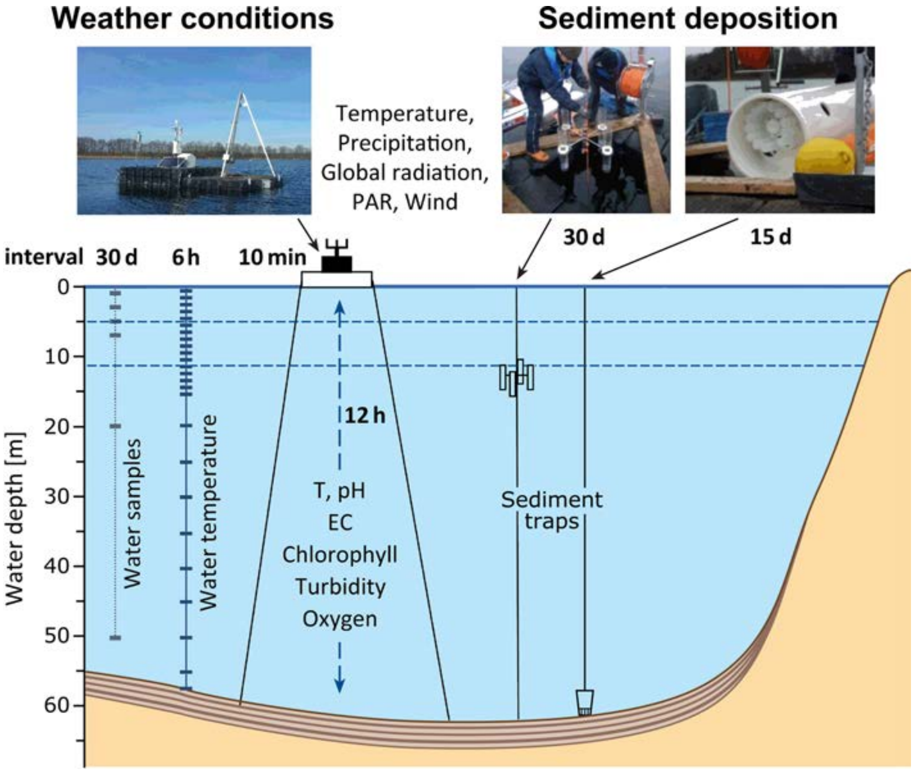

Figure 6. Monitoring concept and installations at Tiefer See including a weather station, automatic water probes and various sediment traps. PAR: photosynthetically active radiation; EC: electrical conductivity.

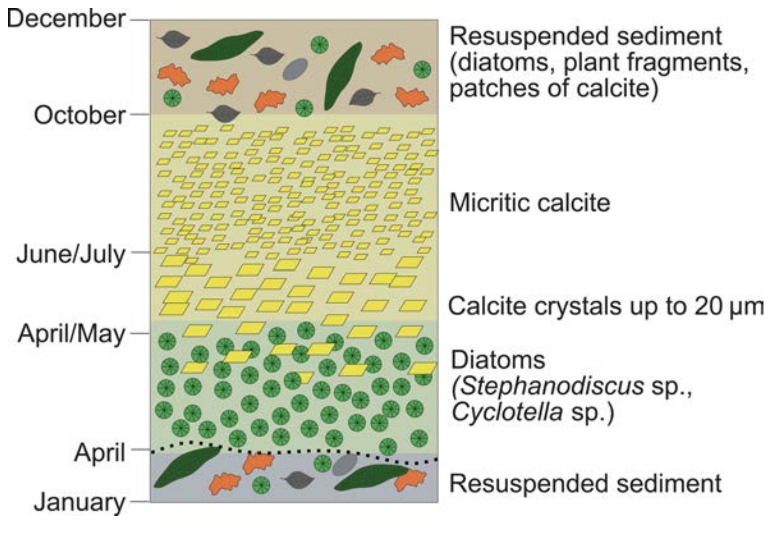

Figure 7. Schematic presentation of sedimentation during the course of the year and division of three seasonal sublayers (modified from Roeser et al., 2021a).

cant lake level responses after precipitation events (Van der Maaten et al., 2015). Large parts of the Hinnensee surroundings in Serrahn are covered by forest. About 75 % of the Serrahn area is covered by Scots pine (*Pinus sylvestris* L.), sessile oak (*Quercus petraea* Liebl.) and European beech (*Fagus sylvatica* L.) forests of different age cohorts. The forest at the northern shore of Hinnensee is an old-growth oak–beech–pine forest. Nature in Serrahn has been protected since the 18th century for hunting and was declared a wilderness conservation area in 1961 (Nationalparkamt Müritz, 2006). It became part of Müritz National Park in 1990, and the park's Serrahn subsection has been designated a UNESCO World

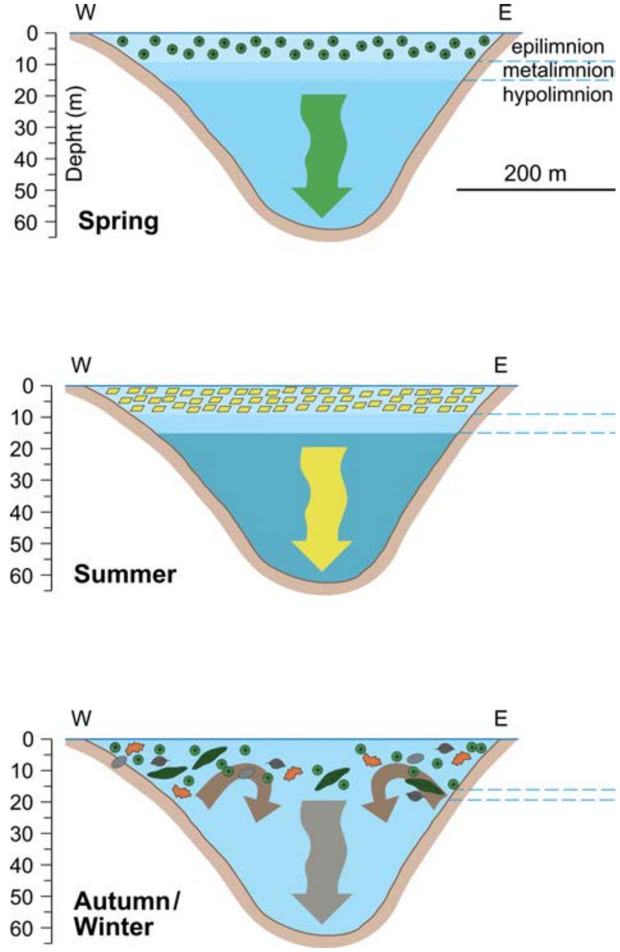

Figure 8. Schematic illustration of dominant seasonal sedimentation processes leading to the deposition of three sublayers that build the modern varves (modified from Roeser et al., 2021a).

Heritage Site for its old-growth beech forest, which contains up to 400-year-old beech stands and over 250-year-old pines (Spiess, 2015). This status as a protected region for such a long period ensures natural or at least near-natural growth conditions.

3.1 Instrumental monitoring setup

The tree-ring observatory Hinnensee comprises instrumental monitoring of the weather conditions including tree-crown throughfall, tree stemflow and leaf wetness, soil moisture and temperature, lake and groundwater levels, tree stem diameter growth, and sap flow (estimate for tree transpiration) (Fig. 9b–e). The measurements are conducted every 30 min.

Soil moisture variability is recorded with 450 sensors at seven different depths between 10 and 200 cm at 15 sites (Fig. 10).

3.2 Selected results

The soil moisture data at the Hinnensee site show the dynamics for the period from 2014–2018 (Fig. 11). The extreme year of 2018 is particularly characterized by above-average wetness until April, followed by strong and continuous drought, which, unlike in normal years, was hardly interrupted by the usual occasional summer rains. From the beginning of June, the minimum of soil moisture prevailed. This minimum was also reached in previous years but always for short periods only. As the water provided by the summer rainfall events is normally absorbed directly by the forest stand, it was to be expected that the trees would suffer particularly from this deficiency in 2018. This should apply first of all to trees that are located further up the slope (right column) as these locations far from the groundwater are drier than directly at the lake, where the distance to the groundwater is only between 0.5 and 4 m (left column).

Not only do the monitored tree species have very different wood anatomical structures (Fig. 12), but also they have different reactions to the extreme conditions of the year 2018.

Figure 13 displays the annual incremental course of wood accumulation of beech, oak and pine that was continuously measured with point dendrometers (Fig. 9c) throughout the growing season of 2018.

While beech is surprising with astonishingly good growth, especially in locations far from groundwater, the other two tree species show strong declines in growth. This is surprising because beech trees are considered to have less resistance to drought (Scharnweber et al., 2011). The main explanation is that the beech trees generally grow faster in the early part of a growing season and also they were still able to benefit from the residual moisture in the soil. Thus, the beech trees had formed a rather normal annual tree ring before the extreme drought set in at the beginning of June 2018. Despite having formed a normal tree ring, the dendrometer data in Fig. 13 clearly show that the growth of the beech trees began and ended earlier in the year 2018. However, the growth curve is steeper than in previous years; i.e. despite a shorter growing period, the beech trees were able to produce a normal annual ring due to their faster growth. For oaks and pines, growth starts at similar times to beeches, with earlier growth for oaks and slower growth for pines and correspondingly narrower annual rings in 2018. For all three tree species it remains to be seen how extremely dry summers or winter-to-spring periods will affect the long-term course of growth. It can be assumed that the drought stress will lead to an undersupply of trees. As a result, the lack of reserves will lead to a delay in growth because after hibernation the trees first have to form new photosynthesis products before wood cells of the following annual rings can then be produced. However, the tree damage caused by the extreme year 2018 was limited and probably mitigated by the soil moisture still available at the beginning of the growing period.

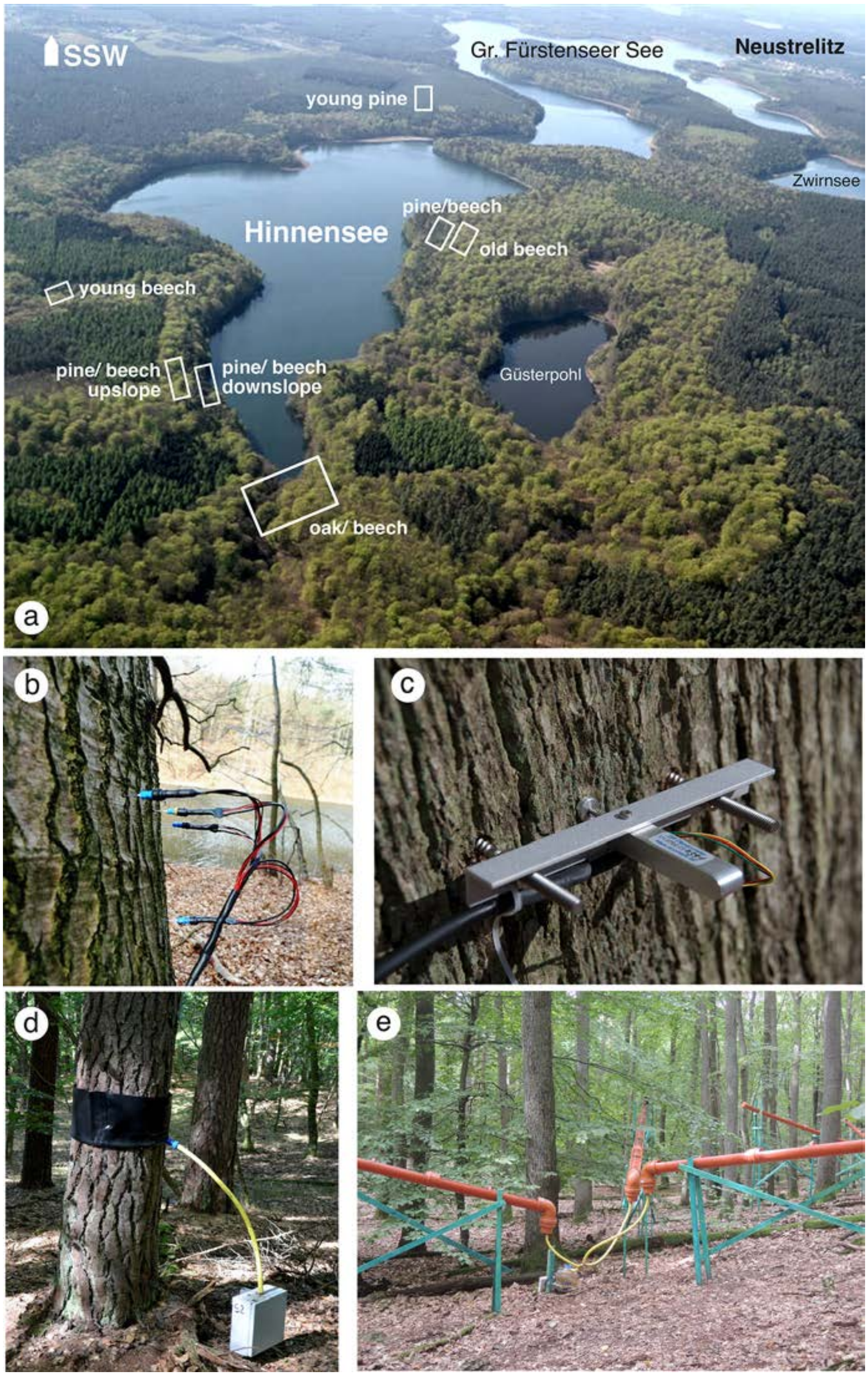

Figure 9. View of the tree-ring and hydrological observatory Hinnensee with its forest monitoring plots **(a)**. **(b)** Monitoring of tree transpiration with sap flow sensors and **(c)** half-hourly stem growth with dendrometers. Forest hydrological monitoring with (among others) **(d)** a stemflow collector and **(e)** canopy throughfall collectors.

3.3 Using tree rings for reconstructions

Several climatological and environmental factors can influence tree growth. Hence, it is a great challenge, from a methodological point of view, to evaluate to what extent and by which processes climatic changes are mirrored in the tree-ring archive, particularly from temperate regions, where the majority of people live. Novel methods and proxies (quantitative wood cell structure analyses and stable isotopes of carbon, oxygen and hydrogen) have been developed to cope

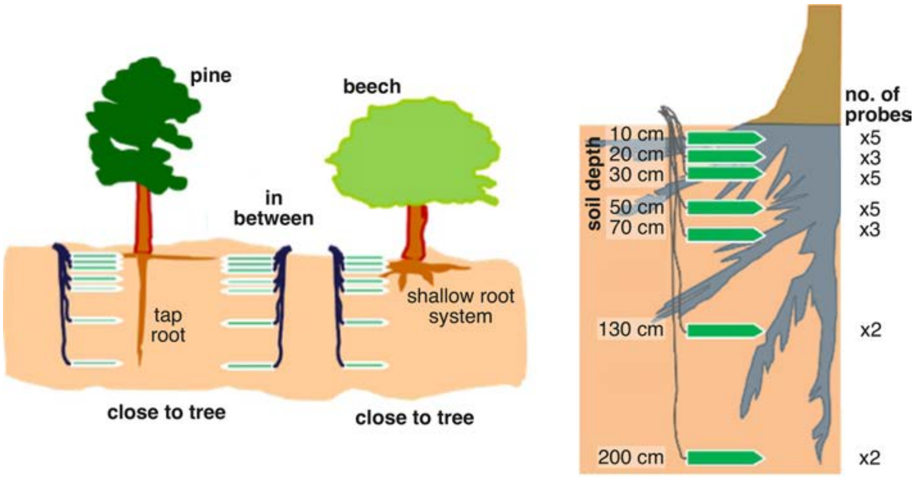

Figure 10. Setup of soil moisture monitoring. Several probes are installed at various rooting depths in between and close to different trees and tree species with different rooting depths.

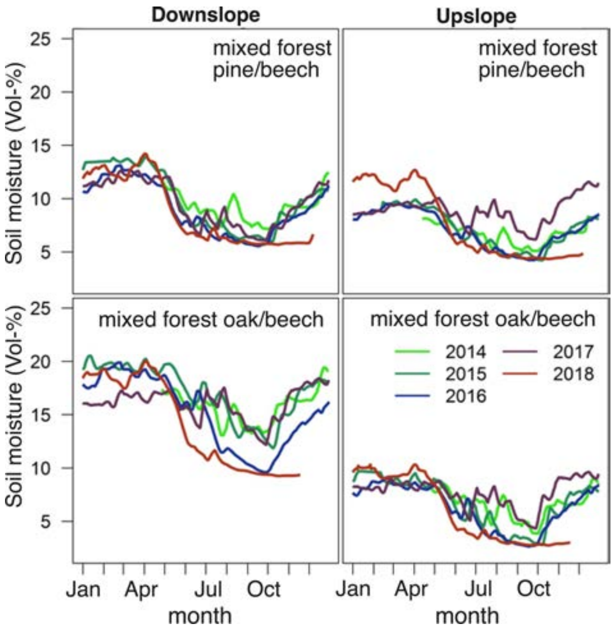

Figure 11. Annual mean soil moisture dynamics for the years 2014–2018 at four monitoring locations around Hinnensee, Müritz National Park.

with this challenge and help to better assess present-day forest health. The monitoring of climate signal transfers from atmosphere and soil into tree rings at Hinnensee is of crucial importance to test, improve and verify these new approaches to enhance our ability to quantify past climatic changes, which is in return necessary to enable better prediction of climate change impacts. It is of particular importance to disentangle climate signals from the multiple local to regional environmental influences acting on the physical and chemical characteristics of tree rings.

For example, the climate signatures of stable carbon and oxygen isotopes in tree rings of Scots pine (*Pinus sylvestris* L.) and sessile oak (*Quercus petraea* L.) in north-eastern Germany do reflect regional hydrological signals in the high-frequency domain (year to year) well. However, long-term trends (decadal to multi-decadal) deviate strongly between oak and pine and carbon and oxygen isotopes. Well-known fractionations of carbon isotopes during photosynthetic uptake of atmospheric CO_2 (c_a; Fig. 14) into tree leaves through their pore openings (stomata) allow the retrospective assessment of leaf-internal CO_2 concentrations (c_i) from tree-ring $\delta^{13}C$ data.

This helps to evaluate the response of forest trees in terms of trends in stomatal aperture and c_i with regard to the rise in atmospheric CO_2 concentrations ($c_a - c_i$; Fig. 15a). While increasing c_a can stimulate photosynthesis and tree growth, it can also help to mitigate drought stress from climate warming as it allows the trees to reduce the apertures of the stomata for reducing transpiration and saving water while keeping c_i and related photosynthesis rather constant.

Proxy and model analysis show that trees actually do a bit of both (Cernusak et al., 2019; Frank et al., 2015): since the beginning of the 20th century they have tended to close the stomata moderately with c_a increase, allowing them to slightly constrain water loss by transpiration and also increase photosynthetic rates to a certain extent. This is expressed in a constant c_i/c_a ratio as shown by a number of pine trees from a European tree network (Fig. 15b).

A strong response of stomatal closure relative to c_a increase would correspond to a constant c_i scenario, while no stomatal reaction to changing c_a would be reflected in $c_a - c_i$ giving a constant scenario (Fig. 15a) (Saurer et al., 2004). While the majority of European pines follow the moderate path of stomatal response to c_a rise, pines from Hinnensee revealed a distinct period of strong stomatal reaction between

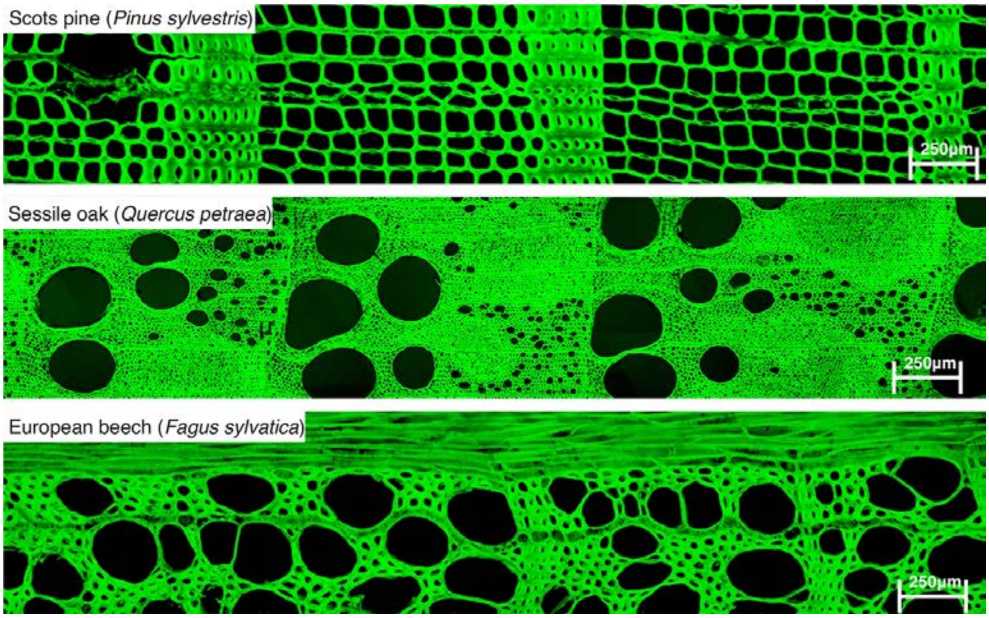

Figure 12. Microscopic images of stem wood of monitored tree species *Pinus sylvestris* (pine), *Quercus petraea* (oak) and *Fagus sylvatica* (beech).

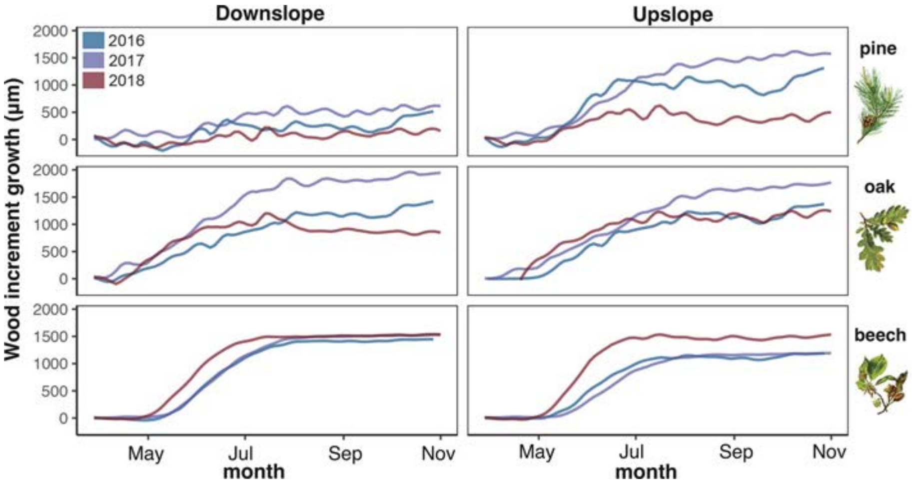

Figure 13. Annual course of wood increment growth of pine, oak and beech (from top to bottom) at site Hinnensee (2016 to 2018). Other years are not shown for better clarity.

1963 to 1992 CE. This indicates an environmental stress on photosynthesis and points to potentially impaired tree vitality, although no external symptoms were reported.

The reconstructed strong stomatal response can most likely be attributed to sulfur dioxide (SO_2) air pollution. During German Democratic Republic (GDR) times, East Germany inflicted high stress on the environment by unfiltered and almost exclusive burning of sulfur-rich lignite in pursuit of independence in the energy sector (Fig. 16; Acker et al., 1998; AG Energiebilanzen e.V., 2020). SO_2 pollution was pervasive in the brown-coal regions of Lusatia and central Germany around Leipzig with their large brown-coal power plants. However, the rural northeast German lowlands were considered to be only marginally affected by the heavy air pollutant emissions prevailing in certain regions south of Berlin until 1990.

Indeed, the forests of Müritz National Park showed no visible external symptoms of reduced forest health during the 1980s, the period of highest SO_2 emissions. But, linking tree-ring δ^{13}C-derived c_i data to c_a changes revealed a previously unknown and unexpected impact of air pollution in this area prevailing particularly from 1963 to 1992 (Fig. 15c). Interestingly, broadleaf oak trees from Hinnensee did not record any SO_2 stress in their tree-ring isotope signature (not shown

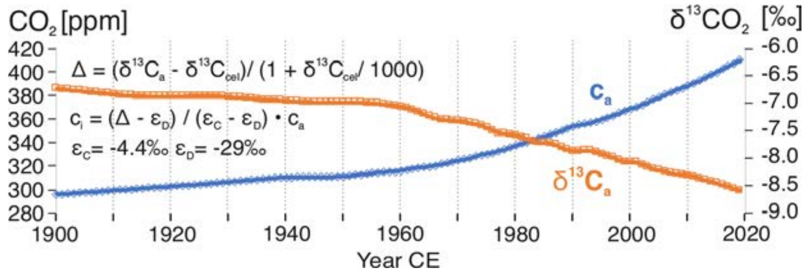

Figure 14. Increase in atmospheric CO_2 (c_a) and corresponding $\delta^{13}C_{c_a}$ since 1900 CE. Data taken from the compilation by Belmecheri and Lavergne (2020). Equations shown are simplifications of the model of carbon isotope fractionation during photosynthesis (Farquhar et al., 1982) from which retrospective estimates of leaf-internal CO_2 (c_i) concentrations from tree-ring $\delta^{13}C$ ($\delta^{13}C_{tree}$) are calculated.

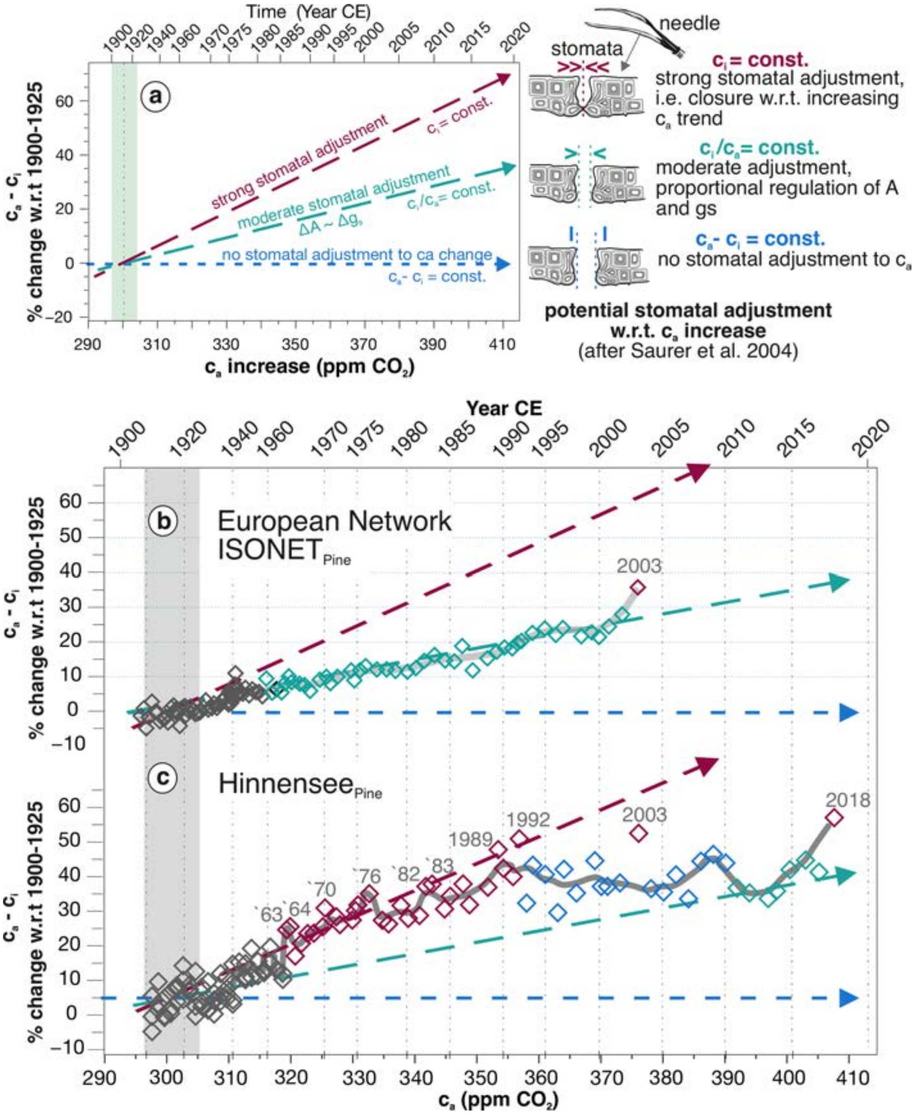

Figure 15. Leaf stomatal response to atmospheric CO_2 rise given as $c_a - c_i$ (percent change with respect to 1900–1925) derived from $\delta^{13}C_{tree}$. **(a)** Three categories of potential stomatal adjustment: strong (c_i is constant), moderate ($c_a = c_a$ is constant) and no response ($c_a - c_i$ is constant). A moderate response is c_a increase is usually observed; hence photosynthetic CO_2 assimilation (A) and stomatal conductance (g_s) are regulated proportionally. **(b)** Average $c_a - c_i$ of a network of pine stands across Europe (ISONET, 1900–2003); **(c)** $c_a - c_i$ of pine from Hinnensee, indicating an episode of environmental stress from SO_2 pollution between 1963–1992 and subsequent recovery, except for extreme drought years in 2003 and 2018. All dates plotted indicate drought years (graphs modified after Helle et al., 2022).

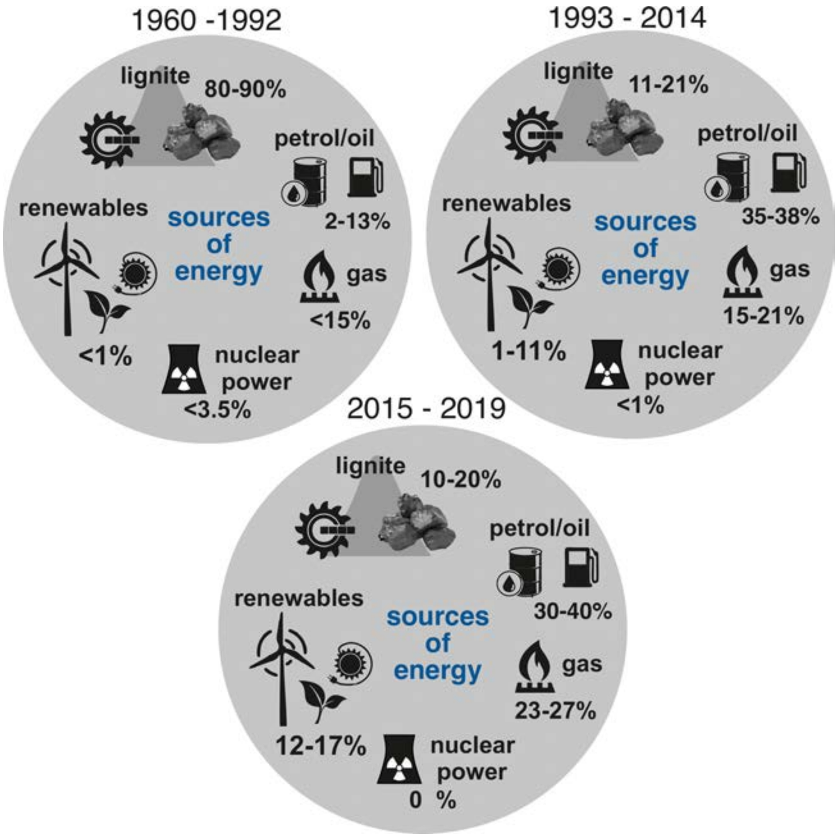

Figure 16. Change in sources of primary energy in northeastern Germany (former GDR) (after AG Energiebilanzen e.V., 2020).

here). This difference between deciduous oak and evergreen pine can be attributed to the seasonality of emissions, which were high in winter and low during summer times without domestic heating and with reduced demand for electricity because of longer daylight periods. Apparently, critical thresholds were passed along with the seasonal changes in SO_2 emissions. Whereas pine needles were damaged by high SO_2 concentrations from enhanced lignite burning during winter or transition periods (autumn, spring), oak leaves were not affected due to low summer SO_2 emissions causing no damage to the photosynthetic system. While this example shows that tree-ring $\delta^{13}C$ is not a direct physical climate proxy and can be influenced by other atmospheric changes like CO_2 rise or air pollution, tree-ring $\delta^{18}O$ does contain a strong and direct hydrological signal averaged over several precipitation events and modified by tree transpiration, which depends on air humidity. Hence, time series of tree-ring $\delta^{18}O$ can be used for lake level reconstructions as shown in Fig. 17 comparing the tree-ring $\delta^{18}O$ chronology from pine at Hinnensee with instrumental lake level measurements of Gr. Fürstenseer See (Hinnensee is the northeastern section of Gr. Fürstenseer See; Fig. 9a).

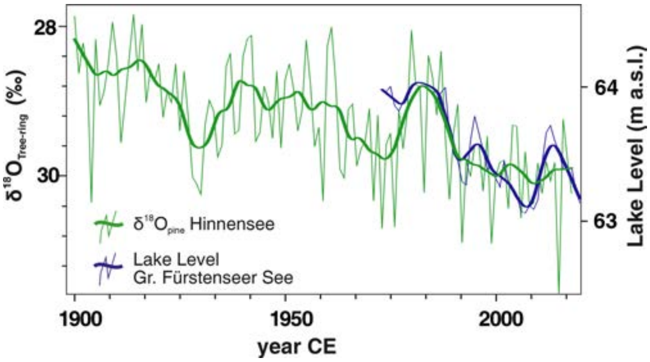

Figure 17. Tree-ring $\delta^{18}O$ of pine vs. lake level measurements of Gr. Fürstenseer See, Müritz National Park (Serrahn section).

4 Highlights

The following can be highlighted:

- Regional coal burning emissions produce non-climatic shifts in tree isotope records.
- A previously undetected episode of reduced tree vitality (1963–1992) due to SO_2 emissions has been identified by tree-ring $\delta^{13}C$ ($c_a - c_i$) in evergreen pine from Müritz

National Park. Deciduous oak was not affected due to seasonality in SO_2 emissions.

- Hydroclimate signals, e.g. lake level fluctuations, are well preserved in tree-ring $\delta^{18}O$ of pine despite air pollution episodes.

- Previous damage from a past SO_2 pollution episode may have increased the vulnerability of pine compared to broadleaf oak to the most recent droughts (e.g. 2018 and 2019).

Data availability. Tiefer See sediment record data are available at https://doi.org/10.1594/PANGAEA.862117 (Dräger et al., 2016). Lake sediment monitoring data are available at GFZ Data Services (https://doi.org/10.5880/GFZ.4.3.2020.003; Roeser et al., 2021b). General information on the TERENO Northeastern German Observatory is available at https://www.tereno.net/joomla/index.php/observatories/northeast-german-lowland-observatory (last access: 16 August 2022) and the TERENO TEODOOR portal (https://ddp.tereno.net/ddp/, last access: 16 August 2022). Soil moisture data are available at https://timeseries.gfz-potsdam.de (last access: 16 August 2022, login required). Tree-ring data and dendrometer data can be requested by contacting dendro52@gfz-potsdam.de. Dendrometer data will be also available at https://timeseries.gfz-potsdam.de but due to technical issues only after September 2022.

Author contributions. AB and TB designed the TERENO Northeastern German Observatory. AB is responsible for the lake monitoring and jointly wrote the manuscript together with IH, with contributions from MJS and GH. IH and GH are responsible for the dendrological monitoring, and TB is responsible for the hydrological monitoring at Hinnensee. BP provided stable isotope data from Tiefer See, and DB analysed dendrological data. BB, MK and SP carried out fieldwork at Tiefer See, including coring, data collection and quality control.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Quaternary and geoarcheology in Lower Lusatia

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Abstract: Open-cast lignite mines in Lower Lusatia provide unique insights into human-induced environmental changes in the Northern European Lowland and improve our understanding of Quaternary landscape dynamics. The excursion will focus on soils and sediments of Late Pleistocene and Holocene age that have been modified by land use since the Slavic Middle Ages. In the vicinity of the open-cast mine Jänschwalde and in the Tauer forest north of Cottbus characteristic remains of historical charcoal production, a ridge-and-furrow system and late Quaternary rubification in soils are presented.

1 Introduction

1.1 Physiographic setting of Lower Lusatia – site 1: lookout at Merzdorf Ostsee (Fig. 1)

Brandenburg is located in the central part of the Northern European Lowland (NEL), which is a zone of extensive plains extending from the North Sea and the Baltic Sea to the foothills of the low mountain ranges of central Europe and extending from the Netherlands to Poland. The plains reach a maximum elevation of 200 m a.s.l. (above sea level). The NEL was mainly shaped by glacial and periglacial processes during the Quaternary (Liedtke and Marcinek, 2002). For Brandenburg, the Brandenburg phase was dated to 34.1 ± 4.6 ka (MIS 3; marine isotope stage), and the global Last Glacial Maximum around 20 ka is represented by the Pomeranian ice-marginal position (Hardt, 2017). Because of sparse or absent vegetation cover and eolian activity, the formation of dunes and coversands was a major geomorphological process in the periglacial areas in the late Pleistocene.

The central morphological feature in Lower Lusatia is the Głogów–Baruth ice-marginal valley separating the landscape formed by Weichselian deposits to the northeast from the Saalian landscape to the southwest.

The climate of Lower Lusatia is continental, with a mean annual air temperature of 8.9 °C and a mean annual precipitation of 549 mm, based on data from the Peitz climate station. Some parts of Lower Lusatia like the Spreewald region are governed by high groundwater tables, but especially near the active open-cast lignite mines the groundwater tables are artificially lowered.

Periglacial deposits and features (Fig. 2) are very abundant, and coversands are widespread, reaching an average thickness of 80 cm and containing ventifacts (Kasse, 2002). The ventifacts indicate a former landscape with sparse vegetation prone to wind erosion and abrading material such as minerals or ice (Kuenen and Perdok, 1962; Meyer, 1986).

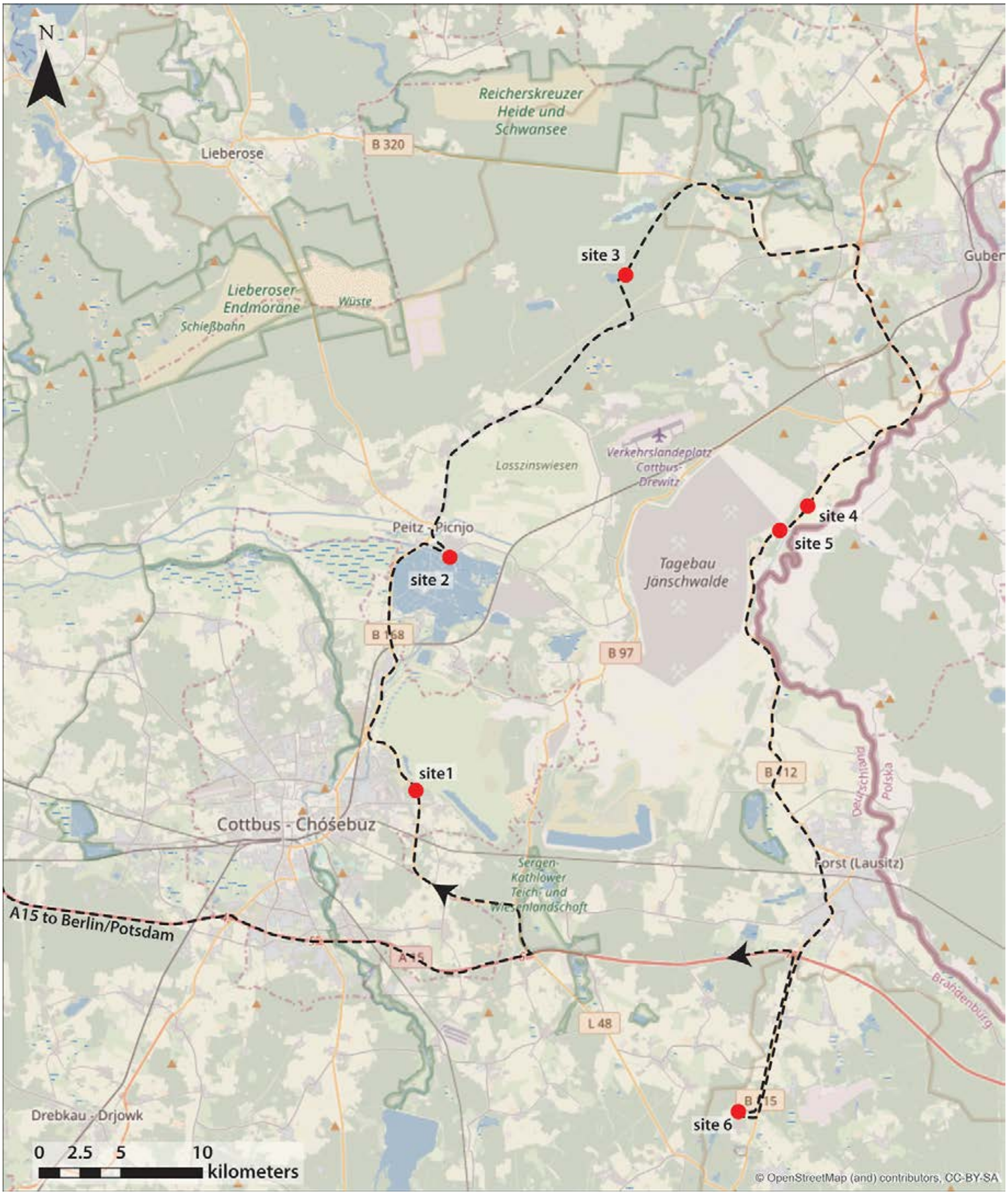

Figure 1. Route of the field trip.

However, wind tunnel experiments prove that only several decades are required to form ventifacts (Kuenen, 1960).

The dominating pedogenic processes in the sandy deposits of Lower Lusatia are brunification and podsolization (Figs. 3 and 4) (Bauriegel et al., 2015a, b; Kühn et al., 2015). Hence, *podsolige Braunerden* (WRB: Brunic Albic Arenosol (Protospodic); World Reference Base for Soil Resources), *Braunerden* (Brunic Arenosols) and Podzols prevail. On loamy substrate *Fahlerden* (Retisols, Luvisols) are present (Kühn et al., 2006). Because of not only the anthropogenic impact on the landscape by (pre)historic land use but also recent activities, initial or weakly developed soils like Regosols and Arenosols are widespread (Gerwin et al., 2015; Nicolay, 2018).

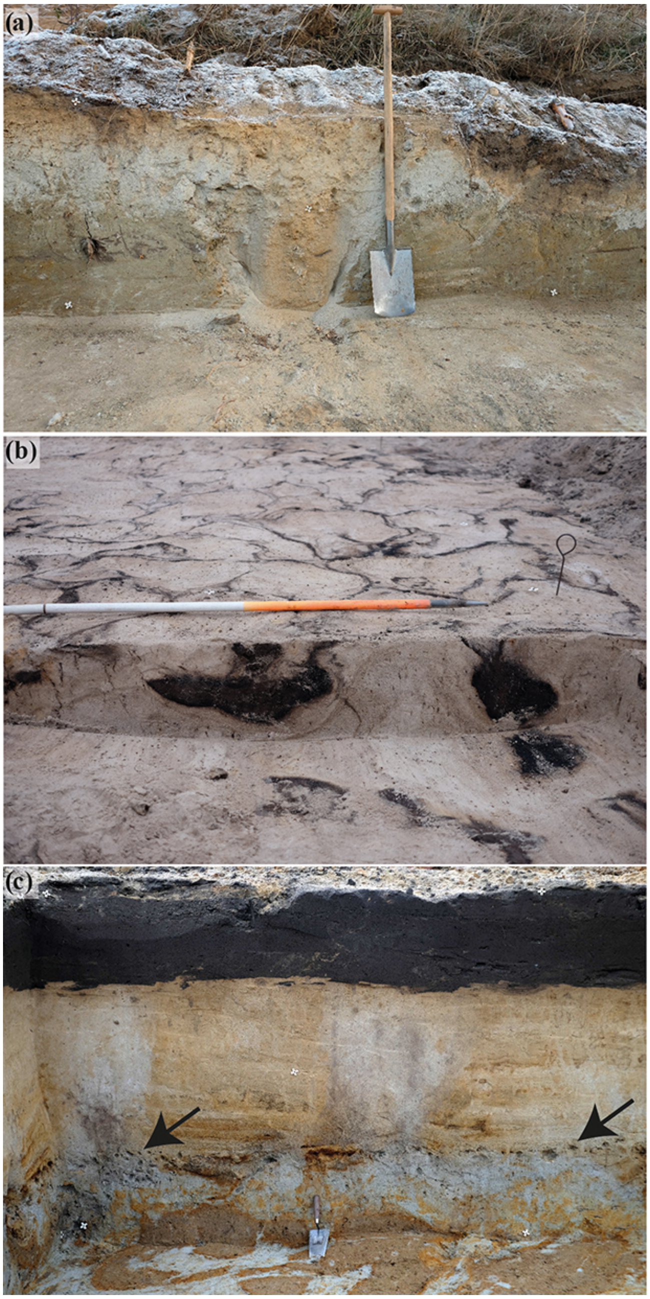

Figure 2. Periglacial features: **(a)** sand wedge near Grießen, **(b)** cryoturbation feature in the open-cast mine Cottbus-Nord and **(c)** a thin stone layer (black arrows) with ventifacts marking the lower boundary of the coversand (near Grießen).

Not only in the coversands but also in the glaciofluvial deposits, brunification is prevailing. Due to the high quartz contents of the sandy substrate and the dry and continental climate, the brunificated subsoils have a brown–pale-brown color and are less pronounced than on sites with loamier parent material. Especially on dunes *Eisenpodsole* are developed (Rustic Ortsteinic Podzol (Arenic) according to World Reference Base for Soil Resources) (Hirsch et al., 2017a), showing the following typical horizon sequence: Ah, Ae, Bsm, Bs and Cv (soil horizons according to Ad-hoc-AG Boden, 2005). *Humuspodsole* (Carbic Ortsteinic Podzol (Arenic)) are often found in areas where groundwater is or was close to the surface. In contrast to the iron-dominated *Eisenpodsol*, the total iron contents (Fe_t) of the *Humuspodsol* is very low, varying around approximately $300\,\mathrm{mg\,kg^{-1}}$ in the illuvial horizons. Especially the illuvial horizons of the *Eisenpodsol* and the *Humuspodsol* can exhibit very strong cementation even limiting the rooting zone. The formation of cemented horizons in Podzols is not restricted to the illuviation of iron chelates as in Bms or Bhms horizons, but cemented horizons can also form in the absence of iron chelates as in Bmh horizons.

1.2 Carp farming in the Peitz lake area – site 2

Carp farming in Peitz has a 450-year-long tradition. The beginnings reach back to the 16th century. Prior to the construction of the fortress Peitz starting in the year 1559, the area south of the city was comprehensively restructured. In this process, the artificial canal Hammerstrom was built to provide the Peitz ironworks with energy and to drive water wheels. Near Peitz, dams were built on both sides of the trench in order to flood the area and thus to make the area impassable. These lakes were already planned as fishing waters. In the official book *Peitzer Amtsbuch* of 1554, the Peitz ironworks and lakes are described as fully functional. In the late 1560s, the lakes were expanded and thus contributed to the fortification of the terrain. Fishery, mainly carp farming, was an important source of income for the administrative district Neumark (Müller, 2013).

1.3 Historical iron production in Peitz – site 2: Peitz ironworks

The Peitz ironworks (1544–1856) operated for more than 300 years. The changing history of the ironworks is described in detail by Müller (2014, 2017). Initially, the ironworks produced munition for the fortress Peitz and the Prussian military. Later on, also cast goods and forged parts were produced for civil use (Hettchen et al., 2014). Until the end of the 17th century, it had been the only ironworks in the Mark Brandenburg. According to Müller (2017), the operation of the Peitz ironworks can be considered an example of a typical Prussian facility. One reason for the founding of the Peitz ironworks was the wealth of commodities in the surroundings and their valorization. The availability of large woodlands and bog iron ore deposits in the direct vicinity were certainly decisive criterions.

The work activities were concerned by contemporary political circumstances, e.g., the Thirty Years' War (1618–1648) and Seven Years' War (1756–1763). Further, the productivity of the ironwork was negatively affected by

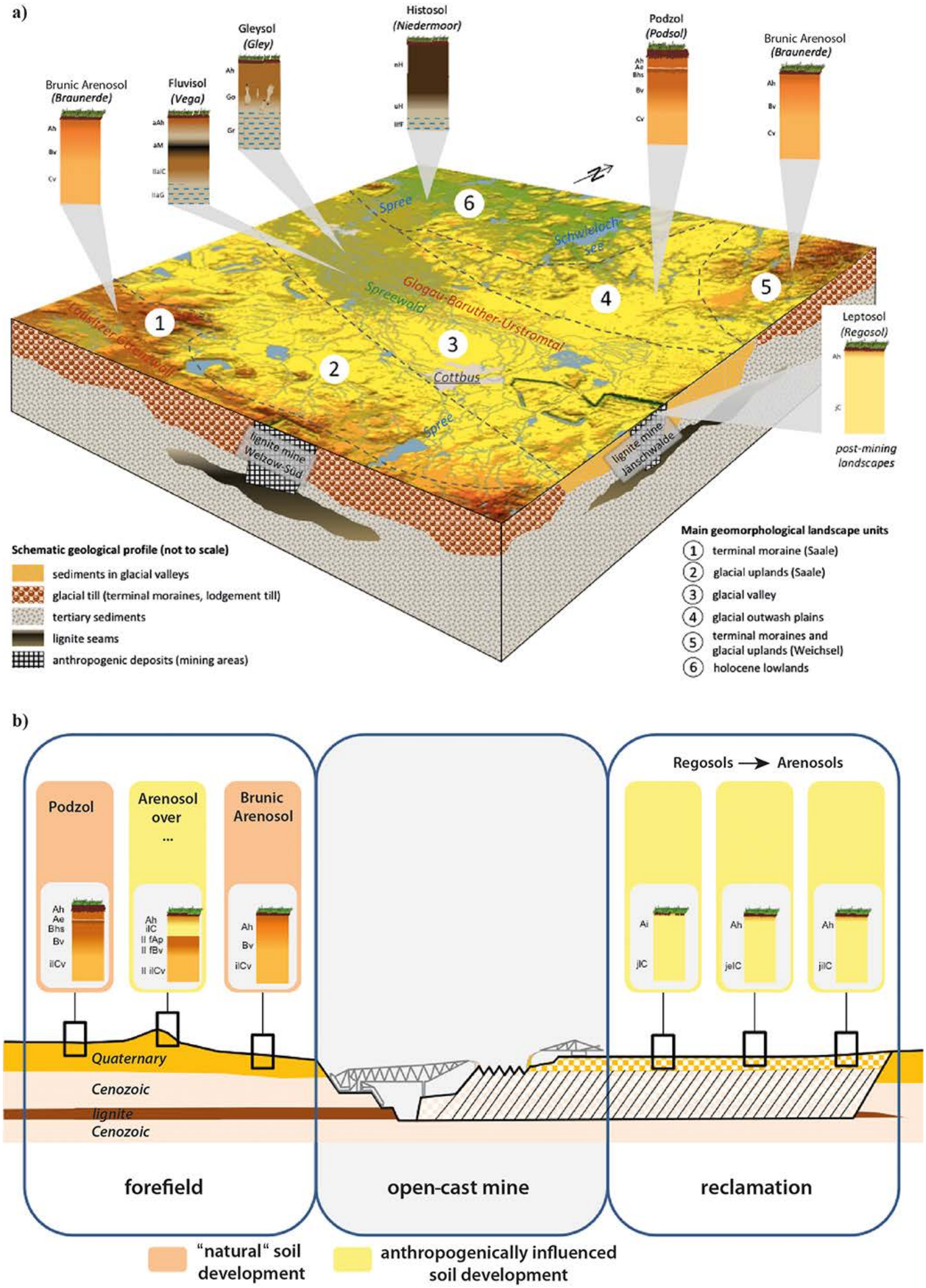

Figure 3. **(a)** Soil geography in Lower Lusatia and **(b)** soils at the open-cast mines. Panel **(a)** drafted by Werner Gerwin. Panel **(b)** translated from German original (Gerwin et al., 2015).

Figure 4. **(a)** Brunic Arenosol; **(b)** Rustic Ortsteinic Podzol; **(c)** Carbic Ortsteinic Podzol; **(d)** young eolian deposits burying a weakly developed Podzol.

structural defects, the silting up of the man-made watercourse Hammergraben, human resources, and particularly unpredictable environmental factors like weather conditions (e.g., frost, ice) or water shortage. Thus, adverse events caused several downtimes resulting in varied numbers of operational weeks from year to year, and correspondingly, the raw materials consumption varied, too. Although the ironworks operated over 3 centuries more or less successfully, wood exploitation was certainly an important factor. The closure of the ironworks in 1858 resulted in a loss of significance for charcoal production in the region. This coincided with the increasing use of lignite and a general loss of importance of wood charcoal.

1.4 Historical charcoal production in Brandenburg – site 3: Waldschule Kleinsee

The starting point for the mapping of relict charcoal hearths (RCHs) was comprehensive archeological excavations in the active lignite mining area Jänschwalde during the 1990s (Fig. 5). Based on the archeological groundwork and the increasing availability of high-resolution lidar data, remote sensing of RCHs based on digital elevation models (DEMs) was started in 2010 (Rösler et al., 2012). Initially, the study area was limited to the territory of the lignite mine Jänschwalde. Over time and with improved remote sensing methods, the mapping area was extended beyond the limits of the former royal Tauer forest to eventually include the whole state of Brandenburg. In the 32 km^2 area of the Jänschwalde mine forefield, about 1400 RCHs had been mapped. Extending the study area to the 109 km^2 area of the royal Tauer forest resulted in a dataset of almost 6000 RCHs (Raab et al., 2019), and finally a total of 47 000 sites were mapped for 10 300 km^2 of forest area in Brandenburg (Schneider et al., 2020). According to our assessments of mapping quality in several ground-truthing studies (Bonhage et al., 2020; Raab et al., 2019), only about 50 % of the RCHs can be captured using the available DEMs with 1 m spatial resolution.

RCHs were found in almost all of the large forest areas in Brandenburg, but their spatial density varied across a wide range (from only a few sites within several square kilometers of the forest to several hundreds of sites per square kilometer). Considerably high RCH densities were found not only in vicinity of the Peitz ironworks (i.e., in the Tauer forest) but also in forests close to other important historic industry sites (e.g., the accumulation of metalworks in Eberswalde and the glassworks in the northern parts of Brandenburg). Nevertheless, the charcoal production field in the Tauer forest is remarkable within Brandenburg because RCHs in the area do not only occur in very high spatial density but also have considerably large diameters of up to 30 m. Similarly, large RCHs were only found in the forest areas south of Eberswalde and, for fewer sites, south of Forst in southeastern Brandenburg. Other areas with very high RCH densities, e.g., in the northernmost part of Brandenburg, are dominated by smaller sites with diameters around 10 m. Very high RCH densities are not only limited to forest areas close to historic industrial sites but also occur in more remote areas, for example, in forest areas north of Berlin and along the Berlin ice-marginal valley between Berlin and Frankfurt (Oder). With only a few exceptions, RCHs in Brandenburg are shaped as slightly elevated platforms with a surrounding ditch, which is the characteristic morphometry of sites on flat landscapes (Raab et al., 2015). For small sites, surrounding ditches are often not observable in DEMs and field surveys. Some larger sites have several pits located concentrically around the platform instead of a continuous ditch, which was similarly described for sites in southern Poland (Rutkiewicz et al., 2019). RCHs shaped as leveled platforms on slopes, an RCH form typically found in low mountain ranges (e.g., Raab et al., 2017; Swieder, 2019), were mapped in only a few individual cases. RCHs are predominantly located in forest areas with sandy parent material, while only a few RCHs occur on silty and clayey substrate and in peat areas within forests. Historical instructions for charcoal production support the interpretation of a preference for hearth construction on sandy soils (von Berg, 1860; Klein, 1836; Krünitz, 1773–1858).

Among other forest areas, those with poorer soil quality (Podzols and Arenosols) clearly show higher RCH densities, similar to observations in Poland (Rutkiewicz et al., 2019). The match between RCH concentration and low-quality soils in Brandenburg might be related to the specific location and spatiotemporal contingency of forest areas in relation to soil properties. In fact, most of the large, historically old (i.e., continuously forested) state forest areas in the region are located in areas with poorer soils (Wulf, 2004). Forests with decent soil quality, for example, Retisols and Luvisols, are often fragmented and distributed over areas dominated by agricultural land use.

The site density in the Tauer forest reaches up to 440 km^{-2}. The site diameters do not show a random spatial distribution pattern but are clustered in hot and cold spots (clusters of large and small sizes). The largest RCH clusters are located north of the village Tauer, east and west of the lake Kleinsee. West of the lake is a cold spot of RCHs consisting of 834 mainly smaller sites. East of the lake is a hot spot, with considerably larger sites but smaller spatial density (Raab et al., 2019).

1.5 Soils on RCHs

The RCH platforms in the Tauer forest show a similar stratigraphy of buried horizons that are overlain by distinct layers of technogenic substrate remaining from charcoal hearth operation (Fig. 5). These remains of the charcoal hearths are dark-gray–black, loose sediment layers rich in charcoal fragments. The thickness of the RCH substrate varies between 20 and 30 cm.

The topsoil horizons buried below the RCH layers (Auh horizons) are often separated by distinct and even boundaries. Sometimes, their topmost centimeters have a slightly more reddish color resulting from thermal alteration of iron (hydr)oxides in some parts of the profiles and thus the appearance of hematite (Hirsch et al., 2017b). The thickness of the buried Ah horizons is often similar to the recent Ah horizons outside of the RCHs. The soil profiles in the remnants of V- to U-shaped ditches surrounding the hearth platforms show infillings with RCH substrate, reaching a depth of approximately 50 cm. The soils of the RCH platforms and ditches are classified as Spolic Technosol over Brunic Arenosol.

According to the German Guidelines for Soil Mapping, the RCHs are classified as Regosol above *Braunerde* (jAh, jilC, IIfAh, IIBv). However, the anthropogenic origins and the inherited and new chemical and physical characteristics of these soil sediments (jilC) are ignored in this classification. Therefore, adapting the M horizon of the German Guidelines for Soil Mapping, allowing for a jM horizon, is suggested. The implementation of a jM horizon would consider the anthropogenic raised charcoal content and indicate the anthropogenic nature (non-erosive translocated soil substrate) of this sediment. Thus, the soils within the RCHs would be classified as a *kolluviale Braunerde* because the jM horizon is < 40 cm thick. Details on RCH soil taxonomy and further data on RCH soil horizons have been compiled by Hirsch et al. (2017b).

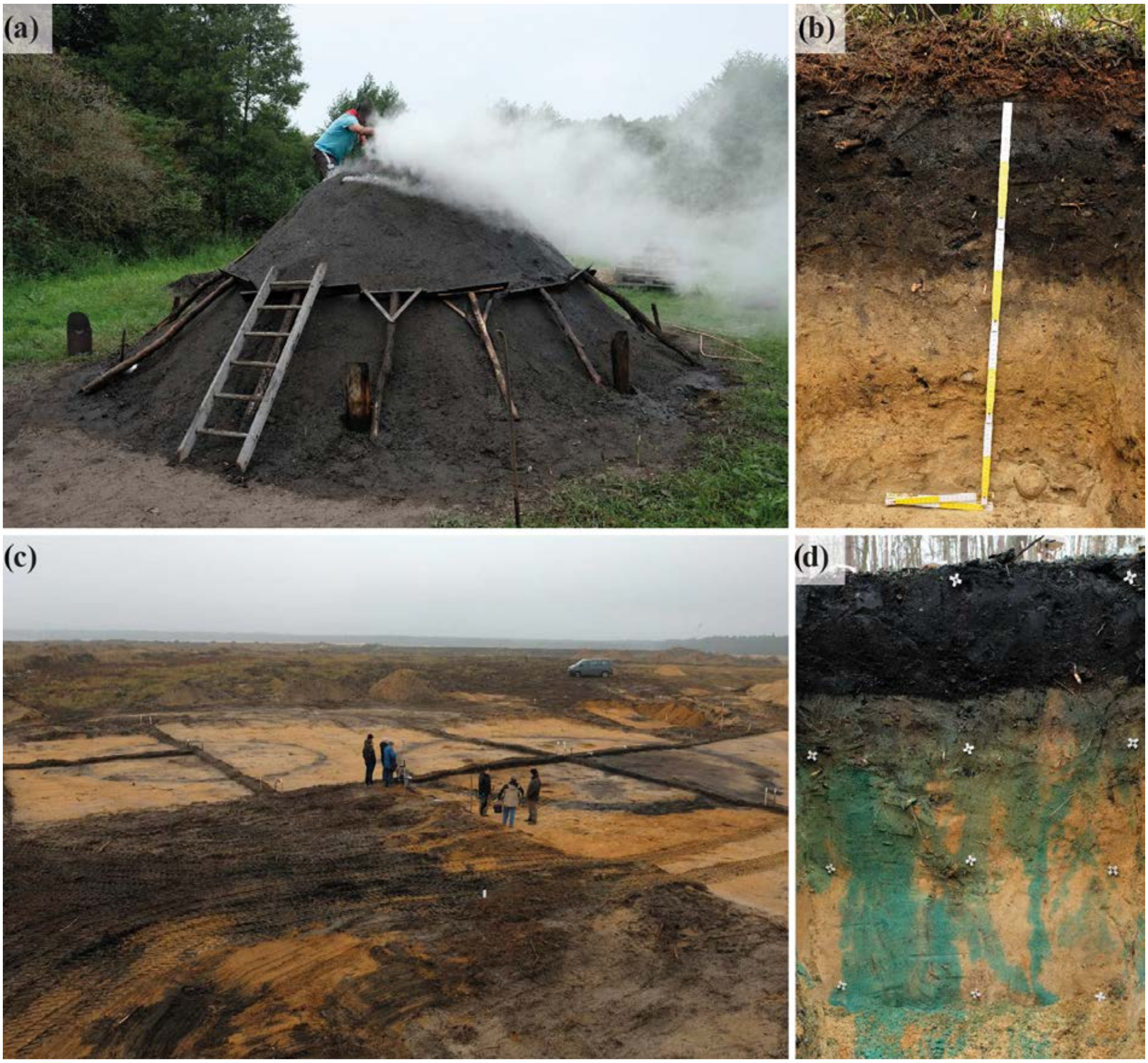

Figure 5. **(a)** Newly constructed charcoal hearth; **(b)** soil profile of an RCH; **(c)** archeological excavations of two RCHs in Jänschwalde; **(d)** dye tracer experiment on an RCH site.

Regarding physical properties of RCH soils, Schneider et al. (2018, 2019a, b, 2020) have recently presented findings from long-term monitoring and further laboratory studies. This research affirms that the technogenic substrate of the RCH is very heterogeneous and contains coarse charcoal fragments of up to 30 wt %. Within the technogenic substrate layers on RCH platforms, the content of coarse charcoal fragments often increases with depth, while ditch fillings often show several layers of sediment with different charcoal fragment contents. Higher root densities were observed in the RCH substrate layers compared to the reference soil outside of the hearths, and a clear preference of root growth in the charcoal-rich substrate, compared with adjacent C horizon material, was observed in the ditch profiles.

Saturated hydraulic conductivity is extremely high for sampled RCHs and reference forest soils because of the sandy parent material. Nevertheless, lower values are observed for the Ah horizons of the undisturbed forest soils, while hydraulic conductivity is clearly higher and more heterogeneous in the RCH substrate and in the RCH-buried Ah horizons. The variability in the hydraulic conductivity data is particularly high in the heterogeneous substrate filling the RCH ditches.

The laboratory data furthermore show a low bulk density and high total porosity for the RCH substrates compared to the soils outside of the RCHs. The bulk densities are significantly lower in the RCH substrate layer and slightly higher in the RCH-buried Ah horizon than in the reference Ah horizons. The pore size distribution, as determined from desaturation water contents, suggests that the higher total porosity of the RCH substrate on the platform and in the ditch profiles is mainly related to higher volumes of coarse and fine pores, while the volume of medium pores in RCH substrates is similar or even lower than in the A horizons of reference forest soils. The high porosity of the RCH substrates is therefore not associated with higher contents of plant-available water per unit volume of soil. Nevertheless, more plant-available water can be stored in the root zone of RCH soils, compared with that of unaffected forest soils, because of the high thickness of the RCH layers and buried A horizons.

Infiltration experiments with a dye tracer (Schneider et al., 2018) showed that water infiltration through RCH substrate layers is limited to very few flow paths under dry antecedent soil conditions, related to the persistent hydrophobicity and heterogeneous structure of the substrates. This observation implies that only small parts of the substrate receive water during infiltration events and therefore that actual plant-available water under field conditions might be considerably lower than indicated by laboratory measurements. In contrast, infiltration experiments for wet antecedent conditions showed that large parts of the RCH substrate layer were almost uniformly wetted during infiltration, and no hydrophobicity was observed in the RCH substrate.

Soil moisture monitoring for two sites in the Tauer forest accordingly showed higher water contents in RCH soils under relatively wet conditions and lower water contents under dry conditions, as well as a more rapid decrease in water contents during drying periods. The results therefore affirm that the legacies of charcoal production increase spatial and temporal variations in soil moisture, which in turn can cause increased variability in ecological site conditions in charcoal production areas.

A potential feedback between soils and vegetation was recently studied by Buras et al. (2020). A dendroecological study with a classic control-treatment design to compare Scots pine growing on RCHs with unmodified soils revealed significantly lower aboveground wood production but systematically higher wood elemental concentrations in RCH trees compared to control trees. Tree height and diameter at breast height were significantly higher for control trees compared to trees growing outside of the RCHs. Tree age as derived from tree ring counts indicated that control and treatment trees originate from the same age cohort. All trees responded negatively to summer temperatures in the year prior to ring formation as well as in the year of growth and positively to summer water availability, indicating drought stress during peak season. XRF (X-ray fluorescence) measurements of tree cores showed that wood chemical properties (Ca, K, Fe and Mn) were consistently different for trees growing on the RCH than the trees outside of the RCHs. These results may indicate a higher investment of Scots pine in belowground tissue to compensate for a lower plant-water availability on relict charcoal hearths.

2 Charcoal-burning trail

The charcoal-burning trail Köhlerpfad Waldschule Kleinsee is the result of the project "Erfassung und Bewertung von vorindustriellen Meilerstandorten in Brandenburg – Ein Beitrag zur Bewahrung, Sicherung und nachhaltigen Nutzung einer historischen Kulturlandschaft" funded by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt, DBU). The project is carried out in cooperation with the Brandenburg University of Technology (BTU) Cottbus-Senftenberg, Brandenburgisches Landesamt für Denkmalpflege und Archäologisches Landesmuseum (BLDAM) and Landesbetrieb Forst Brandenburg (LFB).

By means of four stations, the charcoal-burning trail provides information on charcoal burning in general, historical charcoal production in the Tauer forest, relict charcoal hearths as legacy of historical charcoal burning and current research. The trail aims to reach a wide audience including kindergarten kids, school-aged students, university students, researchers and tourists. Since the expected majority of visitors are 6- to 19-year-old school-aged students, outdoor education plays an important role. Among other things, a charcoal-burning site, including a charcoal hearth and a charcoal burner's hut, have been built. The trail is supported by the local Kienstubbenverein Groß Lindow and the Mosaik-Grundschule Peitz.

3 Ridge-and-furrow systems at Grießen – site 4: historical tillage near Grießen

Ridge-and-furrow systems are a widespread legacy from medieval agriculture, but their usage, size and shape in Europe can vary (Ewald, 1969; Beyaert, 2006; Alcántara et al., 2017). Ridge-and-furrow systems consist of parallel ridges separated by shallow furrows. In northeastern Germany, the ridges are several hundred meters long, but the widths of the ridges of 13.5, 18 or 22.5 m are often a multiple of 4.5 m (4.5 m $\approx$ 1 perch; Bönisch, 2001). The usage of moldboard plows together with the organization of the farmland as strip fields caused the formation of ridge-and-furrow systems (Kittler, 1963; Bönisch, 2001). The ridge-and-furrow system was established in Lusatia in the 12th–13th century before hook or scratch plows were common, and the farmland was arranged in blocks (Bönisch, 2001).

At Grießen (Fig. 6), extensive ridge-and-furrow systems are documented on a historic map (Evert, 1774). Soil mapping shows that topsoils are thicker on the ridges than in the furrows. But soil laboratory analysis shows that the dark-colored topsoils in the furrows contain more soil organic matter (SOM) than the greyish topsoils on the ridges. Due to the higher SOM contents in the furrows, also the bulk density is lower in the topsoil of the furrows than on the ridges. Also, the topsoil in the furrows has a remarkable higher total pore volume. Hence, the effective field capacity is lower in the topsoil of the ridges than in the furrows. Overall,

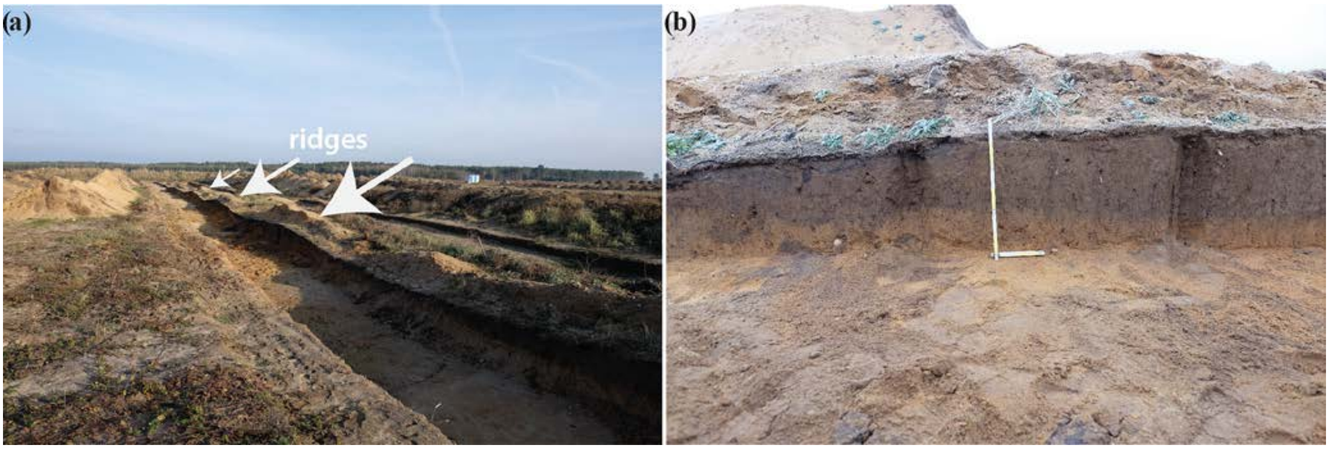

Figure 6. **(a)** Ridge-and-furrow system at Grießen; **(b)** topsoils in the center of a ridge.

the potential rooting zone is thicker on the ridges than in the furrows, but at least due to the SOM enrichment in the last decades the furrows provide better conditions for plant growth by higher SOM contents and a higher effective field capacity. The pedological findings suggest that the construction of the ridge-and-furrow systems was aimed at improving plant growth on the strip-like ridges by building a surface about 40 cm thick and several meters wide for farming. This is underpinned by the archeological findings; at Grießen indications for shoveling are often found in the furrows. Hence, the buildup of the ridge-and-furrow system is associated with piling up substrate to parallel ridges by shoveling (Bönisch, 2013). Also, the higher concentration of pre-medieval artifacts that were found during archeological excavations in the substrate of the ridges underpins the relocation of substrate from the furrows to the ridges (Schneider, 2016). Hence, the furrows not only provided the substrate for the buildup of the ridges but also served as property lines between neighboring ridges. The historic map of Grießen from 1774 indicates that each farmer owned only one strip; therefore the furrow between two ridges served as the property line. This is also underpinned by placed boulders of up to 40 cm that are often situated in the center of the furrows and are interpreted as landmarks.

4 Open-cast lignite mine Jänschwalde – site 5: lookout at Grießen

Despite recent decisions to reduce carbon emissions, power generation from lignite is still a significant economic factor in Germany. Here, the Rhenish and the Lusatian areas are the most important regions for lignite mining. Near Cottbus (Brandenburg), lignite has been mined for decades in the open-cast mines Cottbus-Nord (discontinued in 2015, Fig. 7) and Jänschwalde (still active).

In the open-cast mine Jänschwalde, the lignite is part of the 210 m deep sediment complex from the Cenozoic (Kühner, 2013). Several lignite beds developed due to marine progressions and regressions mainly during the Miocene. In the Jänschwalde mine, the lignite lies in about 50 m depth below the ground surface and is buried by several (deca)meters of glacial and fluvioglacial sediments from the Saalian and Weichselian glaciations. Today, the lignite mine Jänschwalde is operated by the Lausitz Energie Bergbau AG (LEAG). The mining started in 1971 and is planned to end in 2023. The lignite is mined in an open-cast mine with a strip mine approach using a stacker, a conveyer bridge and bucket chain excavators to remove the overburden. Bucket wheel excavators are used to gain the lignite, and the lignite is transported by conveyor belts to the power plant of Jänschwalde about 10 km away.

5 Late Quaternary rubification in soils – site 6: rubification at Klein Kölzig

The formation of hematite in soils (rubification) is a characteristic feature in Mediterranean and tropical environments (Pal et al., 2014; Yaalon, 1997). However, rubified soils have also been reported to occur on late Quaternary sediments within the temperate zone in central Europe (Schwertmann et al., 1982; Jankowski, 2013). The local occurrence of red subsoils on the Late Pleistocene sandy deposits of the NEL invites investigation into the formation and paleoenvironmental significance of these soils (Fig. 8). According to the WRB, these soils are classified as Rhodic Brunic Arenosols or Chromic Brunic Arenosols. In contrast, in the German Guidelines for Soil Mapping these soils are still not considered because of their unclear origins.

At this stop, we present our findings on rubified soils from recent research (for details see Hirsch et al., 2019). In general, we aim to examine and characterize the genesis of the *Fuchserden* in northeastern Germany by (1) analyzing their soil geography and (2) analyzing mineralogical and pedochemical compositions. We also (3) decipher

Figure 7. Conveyer bridge and excavators of the open-cast mine Cottbus-Nord.

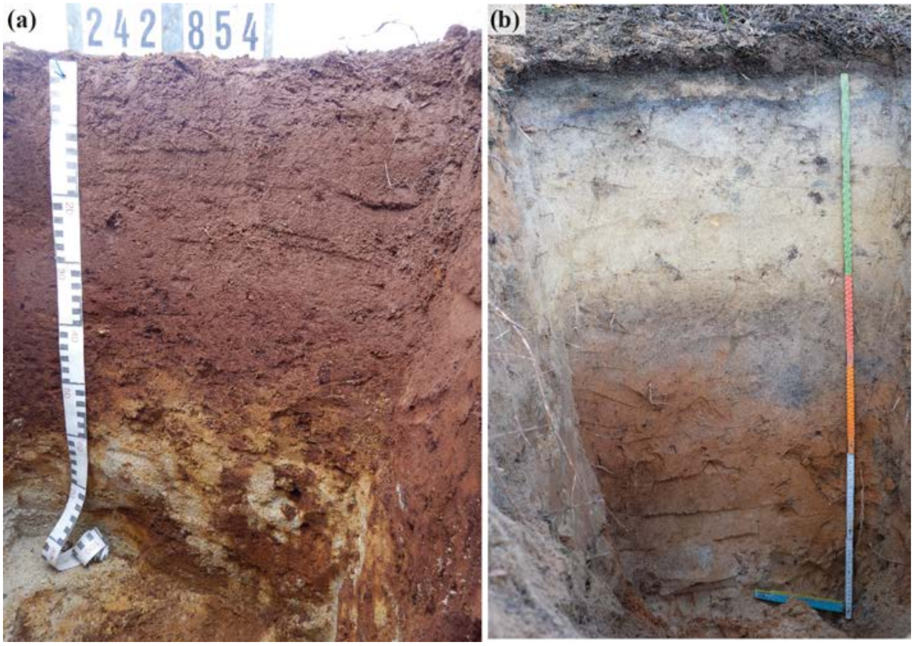

Figure 8. Rubified soils at **(a)** Klein Kölzig and **(b)** rubified soil buried below a dune.

the genetic pathway of these soils and (4) examine their potential genetic relationships with neighboring soils and with soils having similar origins. The analytical approach used here differentiates pedogenic iron (hydr)oxides using a combination of Fourier transform infrared–multiple internal reflection (FTIR-MIR) spectroscopy and sequential sample heating. Together with a comparison of synthetic iron (hydr)oxides, the results of this analytical approach demonstrate that the mineralogy of these Rhodic Brunic Arenosols and Chromic Brunic Arenosols are characterized mainly by hematite; some goethite and minor amounts of maghemite are also present. The results confirm recent findings from Jankowski (2013) that rubification is not primarily a relict process in central European soils, consequently. The high total iron contents in the rubified soils suggest strongly that the iron is allochthonous in origin, emphasizing the importance of lateral inputs of iron compounds in the genesis of these soils. This finding is highly consistent with the "translocation catena" concept (Sommer and Schlichting, 1997); i.e., the Rhodic Brunic Arenosols and Chromic Brunic Arenosols studied here were most likely formed by inputs of allochthonous compounds. The rubified soils examined in this study share some genetic features with other central Europe soils described, such as the *Lockerbraunerden* or the *Ockererden*. Further research should focus on these commonalities and compare the genetic pathways of such soils to support the argument that these soils should be considered in a separate soil class in the German Guidelines for Soil Mapping.

Data availability. Data are available through cited publications of the authors in the reference list.

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