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THE 12II DB OUTCROP SECTION AT SCHÖNINGEN: SEDIMENTARY FACIES AND DEPOSITIONAL ARCHITECTURE

Schöningen (**figs 1-2**) is one of the most important archaeological sites in Central Europe. Since 1992, several Lower Palaeolithic artefacts have been discovered in Middle Pleistocene interglacial sediments in the southern field of the Schöningen open-cast mine (**fig. 2b**). In 1995 hunting spears were discovered, which are thought to be the oldest known complete hunting weapons (Thieme 1997). The Middle Pleistocene interglacial deposits are therefore of particular interest. Although much work has been done on the biostratigraphy and palynology of the interglacial deposits (e.g. Urban et al. 1988; 1991; Urban 1995; 2007), their stratigraphic correlation and their absolute age is still controversial (**fig. 3**; e.g. Litt et al. 2007; Urban et al. 2011) and only little work has been carried out to reconstruct the depositional environment (Mania 1995; 2006).

In this paper we document the stratigraphic evolution and internal facies architecture of the Middle to Late Pleistocene sedimentary succession, exposed at Schöningen 12II DB (**fig. 2b**). The emphasis is placed on the sedimentary facies, facies associations and the analysis of the larger scale stacking pattern of architectural elements. A new depositional model summarising facies features, depositional processes and architectures is proposed that may add to a better understanding of the stratigraphy and the palaeo-environment.

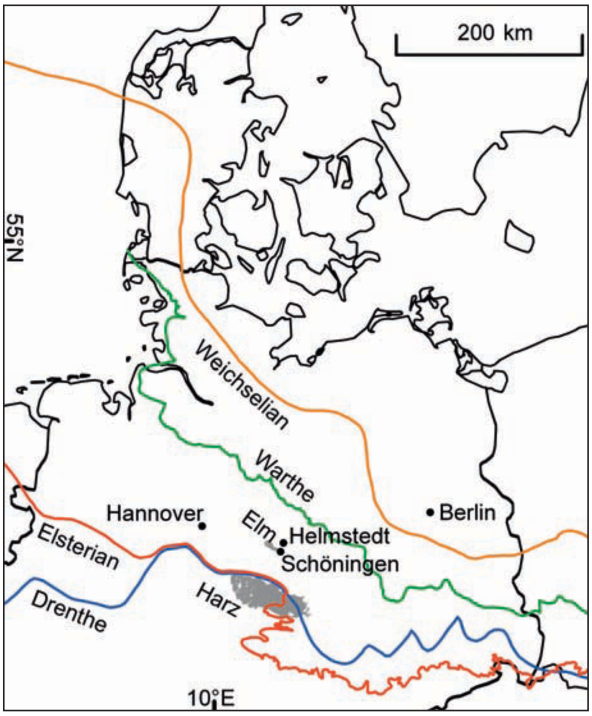

Fig. 1 Location of the study area in Northern Germany and maximum extent of major ice advances. – (Modified from Ehlers et al. 2004).

REGIONAL GEOLOGY AND PREVIOUS WORK

The Schöningen open-cast mine is located in the south-western rim syncline of the Offleben salt wall, which forms part of the 70km long, northwest to southeast trending Helmstedt-Staßfurt salt structure (**fig. 2a**). The basement of the rim syncline is formed by Triassic sedimentary rocks and the main fill of the rim-syncline consists of 360 m thick paralic to marine Palaeogene deposits (Behrend 1927; Brandes et al. 2012). This coal-rich succession is unconformably overlain by 40-60 m thick Pleistocene and Holocene deposits (Elsner 1988; Tschee 1991; Lang et al. 2012).

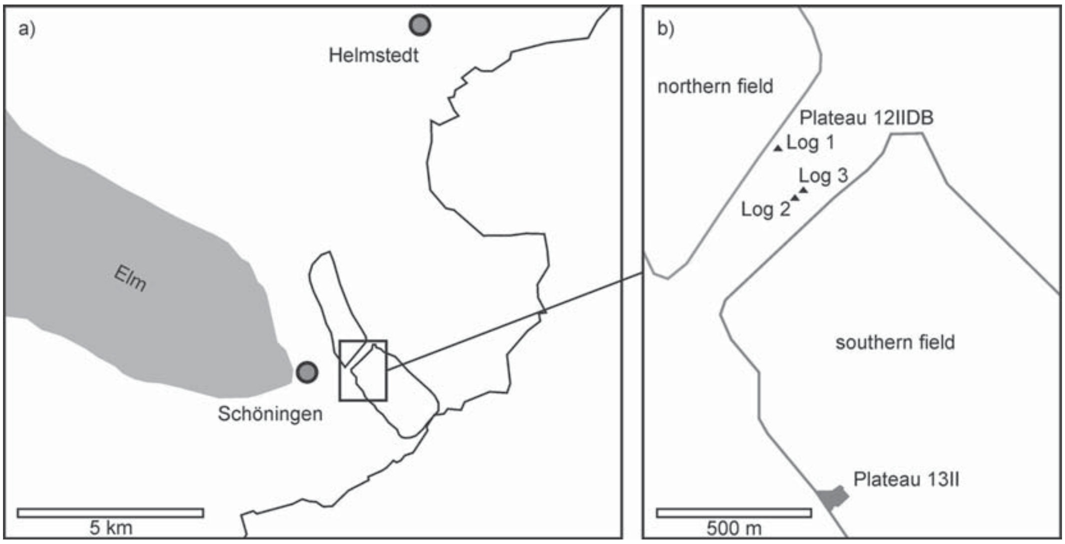

Fig. 2 **a** Map of the study area, showing the extent of the Schöningen open-cast mine. – **b** Detail map of the studied sections in the central part of the Schöningen open-cast mine, showing the locations of the measured logs. – Photo panel 1 (**fig. 9**) covers the outcrop wall behind log 2 and log 3. Photo panel 2 (**fig. 10**) is located immediately southwest of log 1. »Plateau 13II« is the excavation site where the Paleolithic spears were found. – (Map J. Lang).

Northern Germany was affected by three major glaciations during the Elsterian, Saalian and Weichselian glacial periods (**figs 1; 3**). The Elsterian ice sheet covered most of Northern Germany (**fig. 1**; Ehlers et al. 2004) and the ice-advance either occurred during MIS 10 (Litt et al. 2007) or MIS 12 (Ehlers et al. 2004). Two major ice advances are known for the Saalian glaciation. Tills are separated by glacilacustrine and glacifluvial deposits and no interglacial sediments have been found (Litt et al. 2007). The maximum extent of the Saalian ice cover in northwest Germany was reached during the Older Saalian ice advance (»Drenthe« cf. Litt et al. 2007), which probably occurred during MIS 6 (Litt et al. 2007; Busschers et al. 2008) and lasted ~5000 years (Lambeck et al. 2006). The southern margin of the Saalian Drenthe ice sheet extended across most of Northern Germany (**fig. 1**). The second major ice advance of the Saalian Complex, the Warthian, terminated some 50km northeast of the study area. The ice sheet of the Weichselian glaciation did also not reach the study area (Ehlers et al. 2004).

The Schöningen area has been transgressed by both the Elsterian and Older Saalian (Drenthe) ice sheets. The Pleistocene sediments were deposited in a NNW-SSE trending, elongated trough, which is deeply incised into unconsolidated lignite-bearing Palaeogene deposits. The geometry and dimensions of this erosional structure point to a tunnel valley that was incised below the Elsterian ice sheet (Lang et al. 2012). The Elsterian deposits of the Schöningen open-cast mine consist of an up to 40 m thick succession of fine-grained glacilacustrine deposits, coarse-grained meltwater deposits and till (Elsner 1987; Hartmann 1988). Urban et al. (1988), Tschee (1991) and Elsner (2003) reported the presence of two Elsterian tills. The older till is thin (1 m) and has a limited areal extent (150 m), whereas the younger till is up to 10 m thick and has an extent of several hundred meters (Tschee 1991). Tills are separated by glacifluvial deposits (Elsner 2003). The Elsterian glacial deposits are overlain by interglacial lacustrine deposits, which were deposited within the underfilled tunnel valley (Lang et al. 2012). The interglacial deposits have previously been interpreted as infills of shallow basins formed by the melting of dead ice (Elsner 1987) or fluvial channels (Mania 1995), respectively. Three »channels« have been recognized by Mania (1995) between the Elsterian and Saalian glacigenic deposits. According to Mania (1995) »Channel I« is Holsteinian in age and comprises fluvial and limnic deposits with a maximum thickness of 6 m. The fill of »Channel II« is

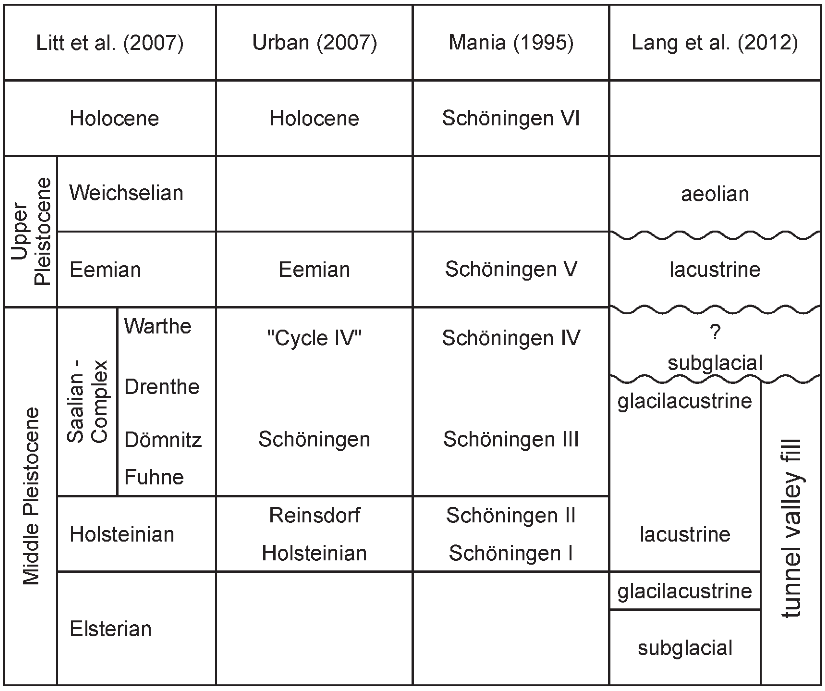

Fig. 3 Stratigraphic chart and depositional environments of the Pleistocene succession at Schöningen. – (Diagram J. Lang).

interpreted to represent the Reinsdorf interglacial (Urban 1995; Mania 2006) and contains the archaeological horizon where the famous palaeolithic hunting spears were found (Thieme 1997). The up to 6 m thick interglacial succession consists of organic-rich lake bottom and deltaic sediments fed by surface runoff shed from the Elm ridge west of the basin (Lang et al. 2012). This succession has been subdivided into five distinct shallowing-upward cycles (»Verlandungsfolgen«, cf. Urban 2007) based on the sedimentary facies and pollen assemblages. However, palynological data suggest that the Reinsdorf interglacial may be also regarded as part of the Holsteinian (Litt et al. 2007). New ^{230}Th/U data support a Holsteinian (MIS 9) age of the »Reinsdorf« succession (Urban et al. 2011). The Schöningen interglacial (»Channel III«) was defined as biostratigraphic unit by Urban et al. (1991) from pollen assemblages and has been correlated with the Dömnitz interglacial (Urban et al. 1991; Litt et al. 2007).

These interglacial deposits are unconformably overlain by glacigenic deposits of the Saalian Drenthe ice advance, which consist of up to 11 m thick coarse-grained meltwater deposits, overlain by a basal till (Elsner 1987; Hartmann 1988). The Saalian glacigenic deposits are overlain by Eemian interglacial deposits, which are up to 7 m thick and consist of travertine and peat (e. g. Elsner 1987; Urban et al. 1988). Weichselian deposits are represented by up to 6 m of loess (Behrend 1927; Elsner 1987; Meyer et al. 1995; Wagner 2011). During the Holocene fluvial deposition and soil formation took place (Elsner 1987; Mania 1995).

METHODS AND DATABASE

Since May 2009 field work was carried out at Schöningen 12II DB (**fig. 2b**). The outcrops were characterised from vertical measured sections and two-dimensional photo panels of the outcrop walls (**figs 7-10**). The logs were measured at the scale of individual beds, noting grain size, bed thickness, bed contacts, bed geometry and internal sedimentary structures. The larger-scale facies architecture was mapped from photo

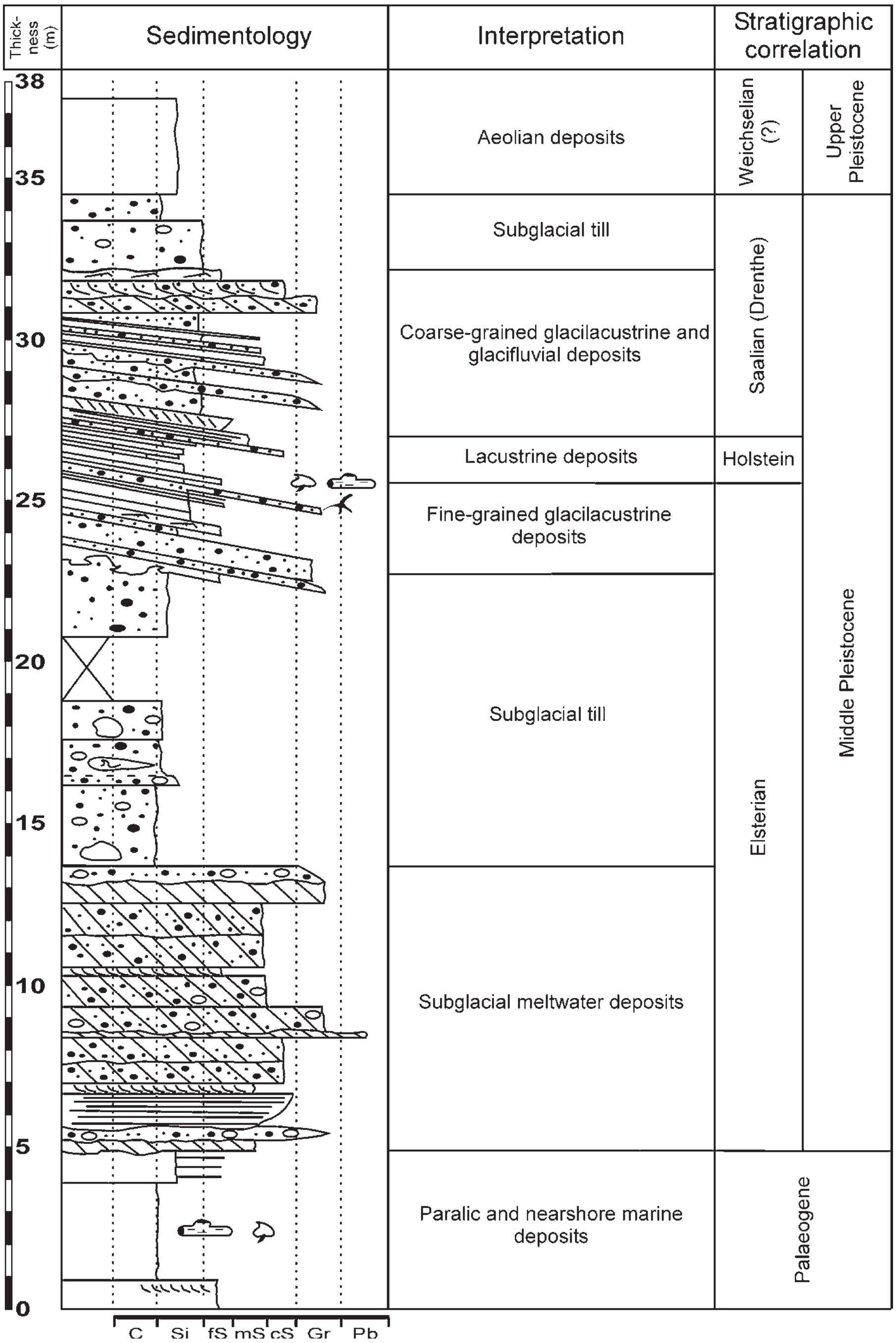

Fig. 4 Log 1: Sedimentological log of the Pleistocene succession measured at the central part of the Schöningen open-cast mine. – For key see **fig. 7**. – (Modified from Lang et al. 2012).

panels. Palaeoflow directions were obtained from cross-bedding and have been corrected for the deformed sections. The clast composition of pebble-sized gravel was determined by K.-D. Meyer for five locations within the studied section.

SEDIMENTARY FACIES AND FACIES ASSOCIATIONS

The exposed section at Schöningen 12II DB is up to 38 m thick (**fig. 4**) and comprises Elsterian, Holsteinian, Saalian and Weichselian deposits. Large parts of the succession are intensely deformed by glacitectonic processes. Thirteen sedimentary facies types (F) were defined on the basis of grain size, bed thickness, bed contacts and sedimentary structures (**table 1**). These facies types were grouped into seven facies associations (FA), based on distinct depositional processes, bed geometries and stratal geometries. A measured log of the complete succession is given in **figure 4. Figures 5-6** show detailed logs of the interglacial deposits.

Glacigenic deposits

Subglacial deposits

FA 1: Massive diamicton

FA 1 consists of matrix-supported, massive diamicton (F 1). The matrix is dark grey or red-brown, carbonate-rich clay to sand. Components are granule- to boulder-sized, moderately rounded to angular and consist of flint, granite, gneiss, sandstone and limestone. Beds are 20 to 250 cm thick and have sharp or deformed contacts. FA 1 is deformed by internal shear planes and contains deformed sand lenses, which are up to 50 cm thick and 150 cm long.

Massive diamicton occur twice within the succession. The lower diamicton is dark grey and very thick-bedded. The upper diamicton is red-brown, medium-bedded and always underlain by a strongly deformed sand and gravel facies (F 2).

The deformed facies (F 2) consists of interbedded medium- to coarse-grained sand and granule to pebble gravel. The fabric is matrix- or clast-supported and the matrix consists of clay to fine-grained sand. Bed thickness is 10 to 80 cm. Bed contacts are sharp and commonly associated with shear planes. Components consist mainly of subangular to angular flint and granite. Thin, deformed layers or lenses of fine-grained sand or diamicton (F 1) are common.

The lower diamicton (**fig. 8a**) is up to 10 m thick and pinches-out towards the northwest. The upper diamicton (**fig. 8f**) is up to 2.5 m thick and sheet-like.

Interpretation

The massive, matrix-supported diamicton is interpreted as a basal till, which is deposited by lodgement and melt-out processes beneath a glacier (Evans et al. 2006). The dominance of clasts with a Scandinavian or Baltic provenance is a further indicator for the glacial origin of the sediment.

The strong deformation of F 2 points to subglacial shearing of soft-sediment (Evans et al. 2006; Aber / Ber 2007). Strongly sheared sediment, which retains some characteristics of the original deposit, was defined as glacitectonite by Evans et al. (2006). Parent material of the glacitectonite was probably the underlying meltwater deposit of FA 3.

The lower grey diamicton is interpreted to represent Elsterian basal till, while the upper red diamicton is interpreted as Saalian (Drenthe) basal till. This stratigraphic classification is primarily based on the stratigraphic position of the two tills, which are separated by interglacial deposits of probably Holsteinian age. The facies associations resemble those described by Elsner (1987) and Tschee (1991) for Elsterian respectively Saalian tills.

Meltwater deposits

FA 2: Cross-stratified sand and gravel

FA 2 consists of light grey to brown, large-scale planar or trough cross-stratifed pebbly sand and gravel (F 5, F 7 and F 8; **fig. 8a**). Cross-sets are 25 to 60 cm thick and have sharp or erosional basal contacts. Pebble-

sedimentary facies	bed contacts	thickness	depositional process
F 1: massive, matrix-supported diamicton Massive, matrix-supported diamicton. Clasts consist of pebbles to cobbles with some boulders. The matrix is a sandy clay. Deformed sand lenses or layers are common.	sharp, gradual or faulted	20-250 cm	subglacial plastering and melt-out of glacial debris (Evans et al. 2006)
F 2: deformed beds Silt to coarse-grained pebbly sand. Original structures deformed into subhorizontal shear planes and boudins. Penetrated by streaks of diamicton.	faulted	10-80 cm	intense soft-sediment deformation by glacitectonic shearing (Evans et al. 2006)
F 3: massive, matrix-supported gravel Massive, matrix-supported granule to pebble gravel. The matrix is silty clay. Rare occurence of undeformed sand intraclasts (up to 10 cm in diameter).	sharp	10-85 cm	deposition by cohesive debris flows (Mulder / Alexander 2001)
F 4: massive, clast-supported gravel Clast-supported, massive granule to pebble gravel with some cobbles. The matrix is fine- to medium-grained sand.	erosional	20-65 cm	deposition by hyperconcentrated density flows (Mulder / Alexander 2001)
F 5: planar cross-stratified gravel Granule to pebble gravel with rare cobbles with planar cross-stratification. The matrix is fine- to medium-grained sand.	erosional	20-80 cm	deposition by turbulent, high-energy tractional currents (Allen 1984)
F 6: planar-parallel stratified pebbly sand pebbly sand with planar cross-stratification	sharp or erosional	5-30 cm	deposition by turbulent, high-energy tractional currents (Allen 1984)
F 7: through cross-stratified pebbly sand Pebbly sand with through cross-stratification. Troughs are 50 to 120 cm wide oblique to flow.	erosional	25-40 cm	deposition by 3D dunes under turbulent, high-energy tractional currents (Allen 1984)
F 8: planar cross-stratified pebbly sand pebbly sand with planar cross-stratification	erosional	35-140 cm	deposition by 2D dunes under turbulent, to high-energy tractional currents (Allen 1984)
F 9: ripple cross-laminated sand Fine- to medium-grained sand with ripple (planar or trough) cross-lamination, partly forming climbing bedsets. Ripple troughs are 5 to 10 cm wide oblique to flow.	sharp, gradual or loaded	5-55 cm	deposition by of 2D or 3D ripples under turbulent, low-energy currents (Allen 1984); the occurence of climbing ripples points to high rates of sedimentation and waning flows (Allen 1984)
F 10: mud and fine-grained sand alternations Alternations of clay, silt and fine-grained sand. Beds are massive, planar-parallel or ripple cross-laminated. Ripples are planar or trough-shaped and partly form climbing bedsets. Rippple troughs are 5 to 15 cm wide oblique to flow. Scattered granules and pebbles occur rarely.	sharp, gradual or loaded	1-40 cm	deposition by waning, low-energy turbulent currents and suspension fall-out (Mulder / Alexander 2001). Scattered granules and pebbles are interpreted as ice-rafted debris (Eyles / Eyles 1992).
F 11: massive, planar-parallel or ripple cross-laminated silt or sand with plant material Organic-rich silt to fine-grained sand. Beds are massive, planar-parallel or ripple planar cross-laminated. Bivalves, plant and wood debris are common.	sharp, gradual or loaded	5-25 cm	deposition by waning, low-energy turbulent currents or suspension fall-out (Mulder / Alexander 2001)
F 12: peat massive or stratified plant and wood debris	sharp or gradual	5-40 cm	peat forms by the accumulation of plant debris in bogs, swamps or shallow lakes (Talbot / Allen 1996)
F 13: massive silt very thickly bedded, massive silt	sharp	100-400 cm	deposition by aeolian suspension fall-out (Collinson et al. 2006)

Tab. 1 Classification of sedimentary facies.

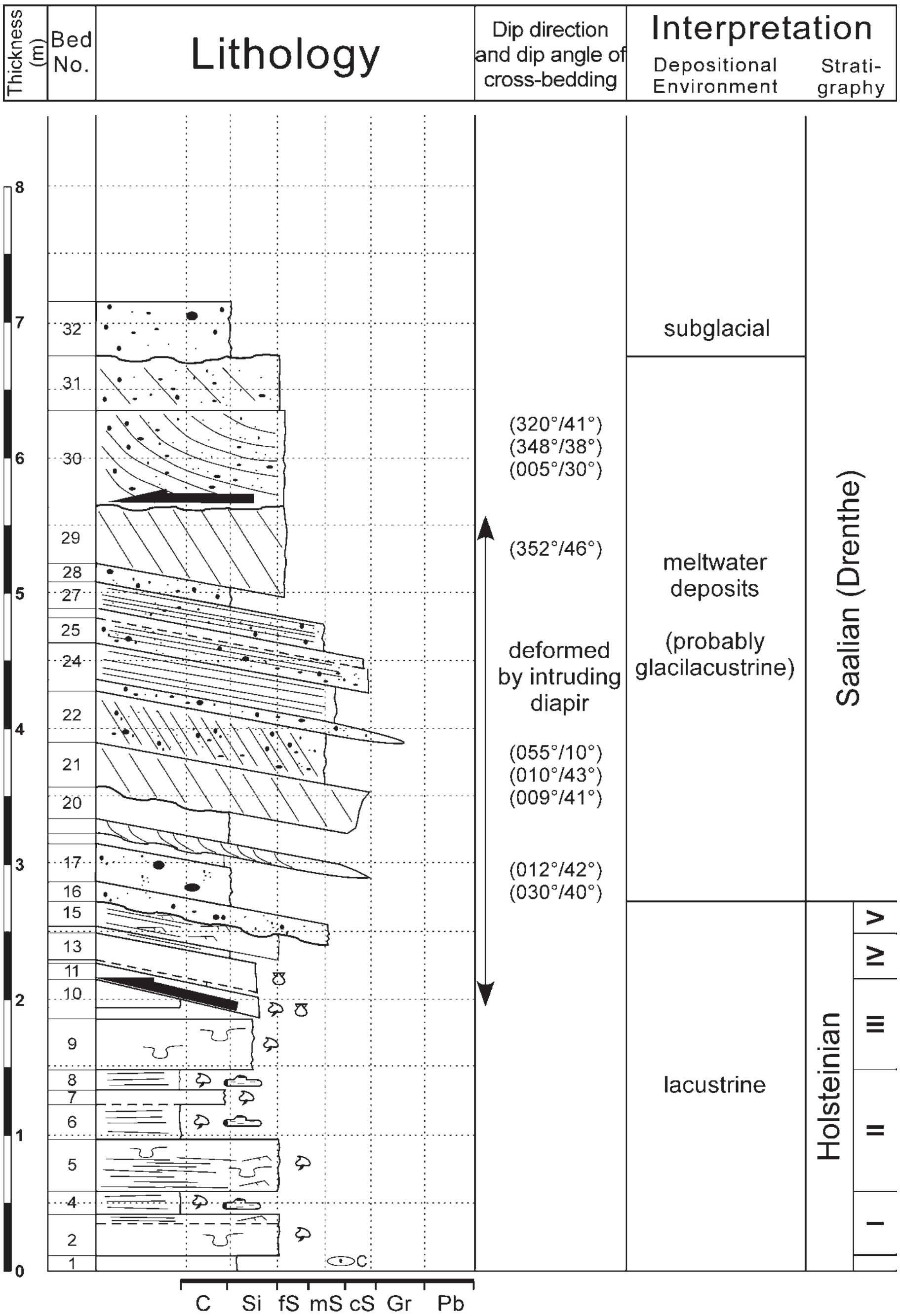

Fig. 5 Log 2: Detailed sedimentological log of the Holsteinian to Saalian succession. Shallowing-upward cycles within the interglacial succession are labelled I to V. The location of Log 2 is shown in **fig. 2 b**, **fig. 9** shows the lateral relation to log 3. – For key see **fig. 7**. – (Diagram J. Lang).

to cobble-sized components are subrounded to subangular. Most clasts (72-82%) are derived from Scandinavia or the Baltic area. Minor proportions of clasts are derived from the adjacent Mesozoic sedimentary rocks (12-17%) and Palaeozoic (6-10%) basement rocks (pers. com., Klaus-Dieter Meyer). Armoured clasts of dark grey diamicton (15 cm in diameter) occur rarely. Abundant lignite fragments contribute to the brown colour of some beds. Within the cross-bedded sand and gravel massive, clast-supported, normally graded gravel lenses (F 4) occur. These lenses have erosional bases and are up to 50 cm thick and up to 6 m wide.

Deformation in FA 2 is rare and only some normal faults with offsets of 10 to 50 cm are present. FA 2 is 9 m thick and palaeoflows, obtained from cross-bedding, were from the northeast and east. The lateral extent and geometry of FA 2 could not be measured.

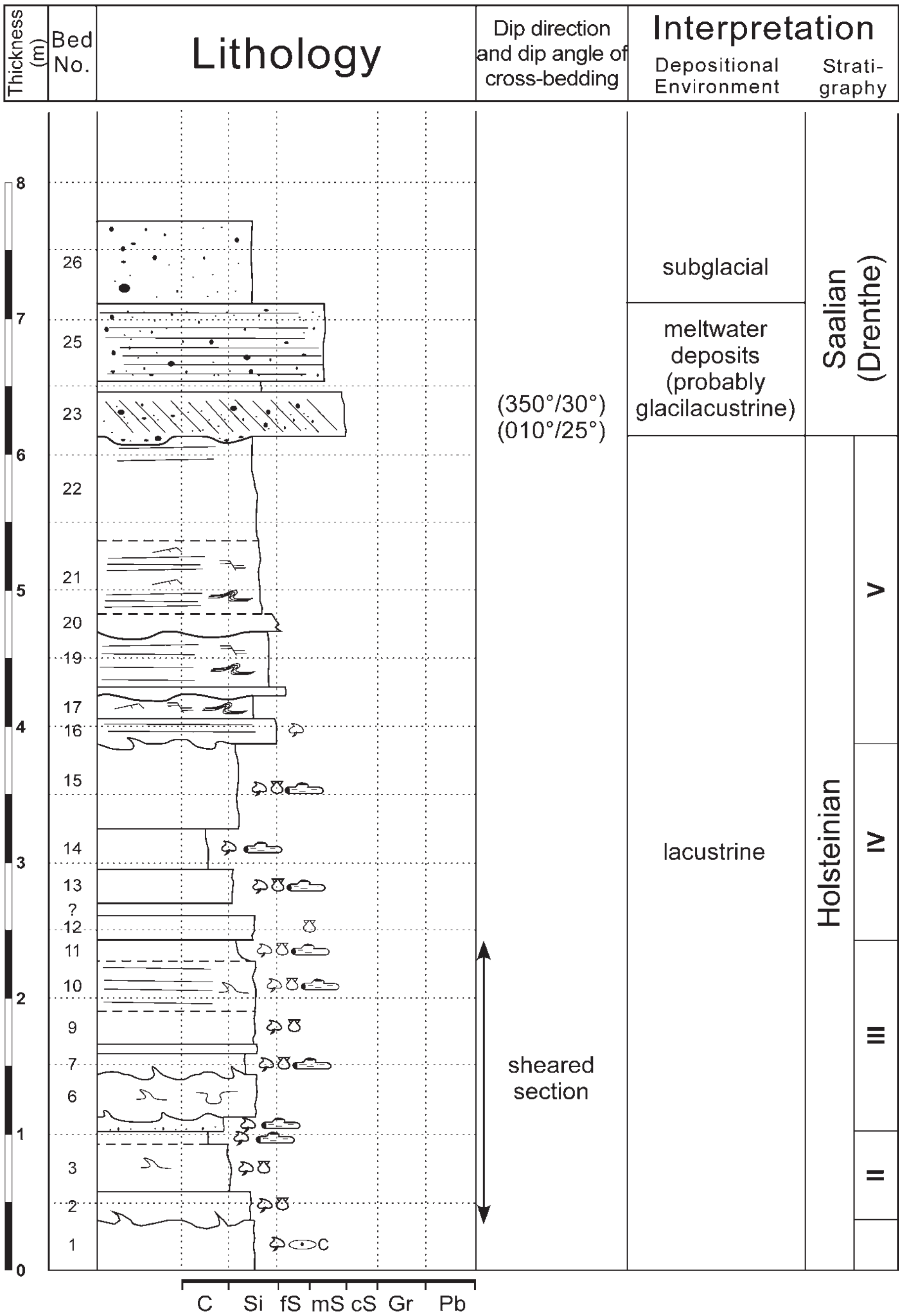

Fig. 6 Log 3: Detailed sedimentological log of the Holsteinian to Saalian succession. Shallowing-upward cycles within the interglacial succession are labelled I to V. The location of Log 3 is shown in **fig. 2b**, **fig. 9** shows the lateral relation to log 2. – For key see **fig. 7**. – (Diagram J. Lang).

Interpretation

Large-scale planar and trough cross-stratified, poorly sorted sand and gravel point to deposition of 2D and 3D dunes by high-energy, turbulent tractional flows (Allen 1984). Erosional bed contacts and resedimented clasts of lignite and diamicton are indicative for the erosive potential of these flows. The intercalated massive gravel lenses are interpreted to represent deposits of non-cohesive debris flows (Postma / Cruickshank 1988; Mulder / Alexander 2001). FA 2 is interpreted as proglacial meltwater deposit. The depositional environment is difficult to reconstruct since limited outcrop conditions prevented the detailed analysis of architectural elements. Therefore these meltwater deposits may either represent glacifluvial (e. g. Miall 1996) or coarse-grained glacilacustrine deposits (e. g. Lønne / Nemec 2004).

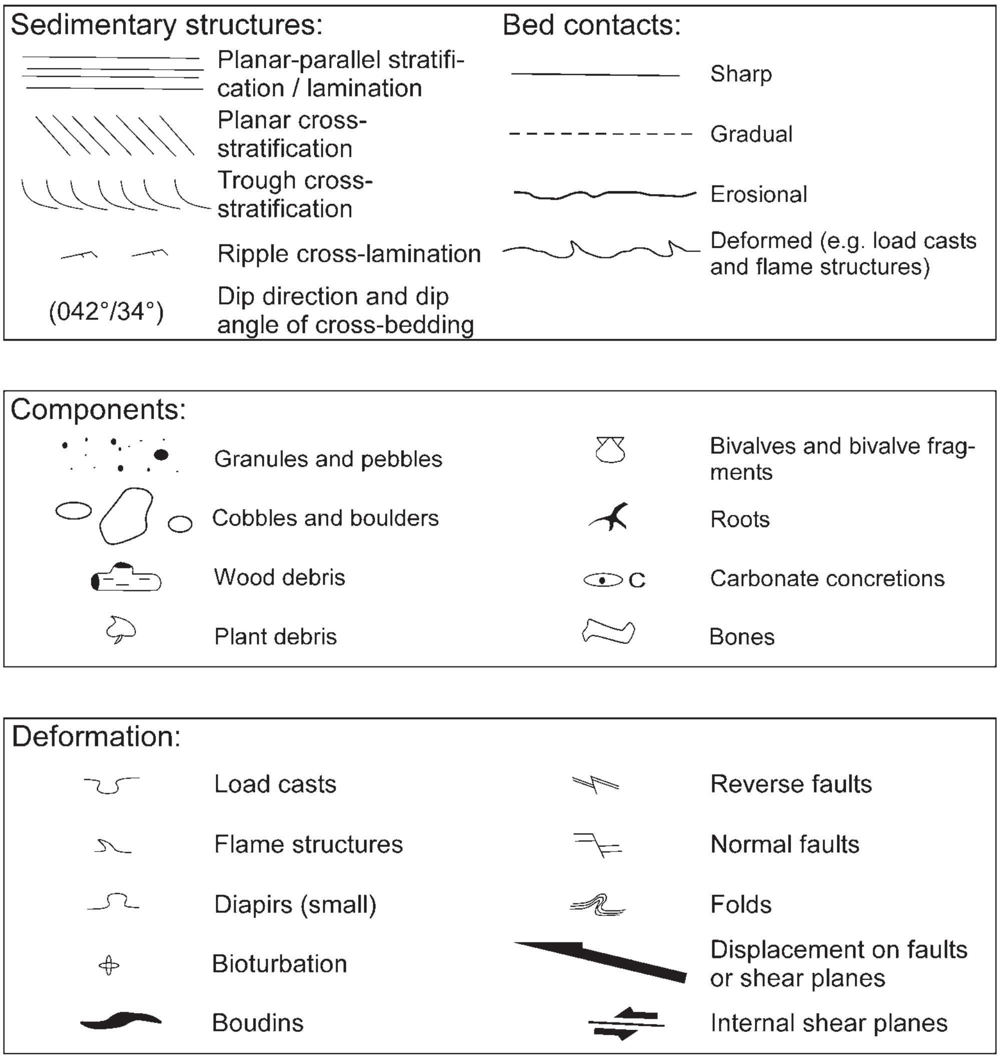

Fig. 7 Key for the sedimentological logs.

FA 3: Planar-parallel, cross-stratified and massive sand and gravel

FA 3 consists of planar-parallel, planar or trough cross-stratified pebbly sand and gravel (F 5, F 6, F 7 and F 8; **fig. 8e**) interbedded with massive, matrix-supported gravel (F 3) and ripple cross-laminated, fine-grained sand (F 9). Beds are 5 to 80 cm thick and bed contacts are sharp or erosional. Granule- to cobble-sized components mainly consist of moderately rounded to subangular granite, flint, sandstone and limestone.

Beds of massive, matrix-supported gravel (F 3) are commonly intercalated. The gravel is granule- to pebble-sized with rare cobbles, supported by a matrix of clay to silt. Components are moderately rounded to angular. Clasts derived from Scandinavia or the Baltic area amount to 62-67%. Clasts derived from the adjacent Mesozoic sedimentary rocks (mostly Triassic limestone and sandstone) amount to 27-33% and from Palaeozoic basement rocks amount to 5-6% (pers. com., K.-D. Meyer). Undeformed sand intraclasts are common (up to 10 cm in diameter). Beds are 10 to 85 cm thick and have sharp basal contacts.

In some locations ripple cross-laminated, fine-grained sand to silt (F 9) is intercalated. These intercalations are lens-shaped, up to 150 cm thick and have a lateral extent of up to 15 m (**fig. 10**). Fine-grained sand intercalations are strongly deformed by load casts and dewatering structures.

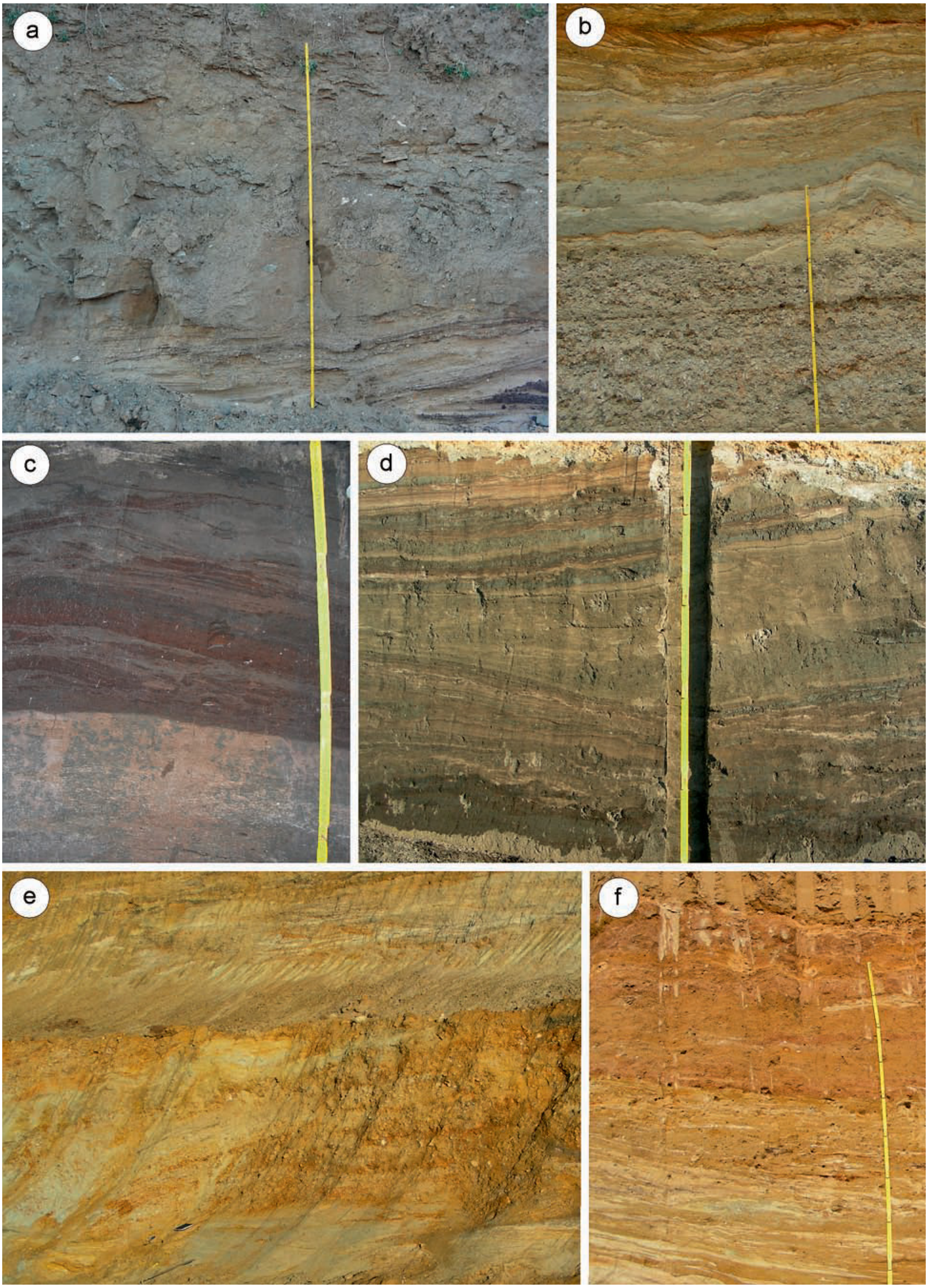

Fig. 8 Facies associations: **a** Elsterian basal till (FA 1), unconformably overlying cross-stratified sand (FA 2). – **b** Elsterian glacilacustrine deposits (FA 4) consisting of massive gravel, silt and cross-stratified sand. – **c** Holsteinian lacustrine stratified peat and massive silt (FA 7). – **d** Holsteinian lacustrine planar-parallel and ripple cross-laminated silt (FA 6). – **e** Saalian meltwater deposits (FA 3), consisting of planar-parallel and cross-stratified sand and gravel. The lower part displays tangential bedding, while the upper part is subhorizontally bedded. – **f** Saalian basal till (FA 1), consisting of highly deformed sand and gravel and massive diamicton. – (Photos J. Lang).

FA 3 is usually arranged into northwest- to southwestward dipping clinoforms. The clinoforms have dip angles between 5° and 25° and can laterally be traced for 3 to 8 m. Clinoforms mainly occur in the lower part of FA 3, while the upper part of FA 3 displays more subhorizontal bedding with common lens-shaped elements. Lens-shaped elements are 1 to 5 m wide, 0.2 to 1 m thick and filled with cross-stratified or massive sand and gravel. The total thickness of FA 3 ranges from 2 to 5 m. The succession is strongly deformed by normal and reverse faults and folds (**fig. 11d**). Due to the intense deformation larger scale architectural elements are difficult to recognize.

Interpretation

The deposition of planar-parallel or cross-stratified pebbly sand and gravel indicates deposition from high-energy, turbulent tractional flows. The occurrence of granite and flint clasts points to a glacigenic origin of the sediment. Low- to high-angle tangential bedding resembles previous descriptions of coarse-grained glacilacustrine delta slope deposits (e. g. Postma / Cruickshank 1988; Nemec 1990) or downstream accretion macroforms within glacifluvial outwash fans (Miall 1977; 1996). Lense-shaped elements are interpreted as infill of minor channels or scours, which may occur on glacilacustrine delta slopes (e. g. Winsemann et al. 2007) or in glacifluvial fans (e. g. Miall 1996).

Intercalated massive, matrix-supported gravel is interpreted as cohesive debris flow deposits (Mulder / Alexander 2001). The lens-shaped bodies of fine-grained sand to silt probably represent episodes when deposition from low-energy processes occurred. The common occurrence of load casts points to high sedimentation rates (McCarroll / Rijsdijk 2003).

The sand and gravel of FA 3 is interpreted as proglacial meltwater deposit, infilling remnants of the interglacial lake basin.

FA 4: Planar-parallel, ripple cross-laminated or massive silt or sand interbedded with massive gravel

FA 4 consists of planar-parallel, ripple cross-laminated or massive interbedded silt and fine-grained sand (F 10; **fig. 8b**). Beds are 1 to 40 cm thick and display sharp or loaded basal contacts. Scattered granules and pebbles occur rarely, their amount decreases upwards within the facies association. Deformation by load casts, ball structures and convolute bedding is common. Palaeoflows were from the north to northeast.

Lenticular or sheet-like beds of massive, clast-supported gravel (F 4) are intercalated and mainly occur in the lower part of FA 4. The gravel has a fine- to medium-grained sand matrix and pebble-sized components may display imbrication. Components are subrounded to subangular. Clasts are derived from Scandinavia or the Baltic area (57%) and from adjacent Mesozoic sedimentary rocks (38%, mostly Triassic limestone or sandstone) and Palaeozoic basement rocks (5%; pers. com., K.-D. Meyer). Beds are 20 to 65 cm thick and have a lateral extent of 1 to 5 m.

Beds of FA 4 dip with 8° to 16° towards the southeast. The thickness of FA 4 is 1 to 4 m. The succession displays a fining-upwards trend with more gravel in the lower part and more sand and silt in the upper part. FA 4 has a lens-shaped geometry. The lateral extent of FA 4 is limited but could not exactly be measured.

Interpretation

Massive, planar-parallel or ripple cross-laminated beds of fine-grained sand and silt are interpreted to result from low-energy turbulent flows and suspension fall-out. Scattered granules and pebbles may represent ice-rafted debris. The occurrence of load casts, ball structures and convolute bedding points to high sedimentation rates (McCarroll / Rijsdijk 2003).

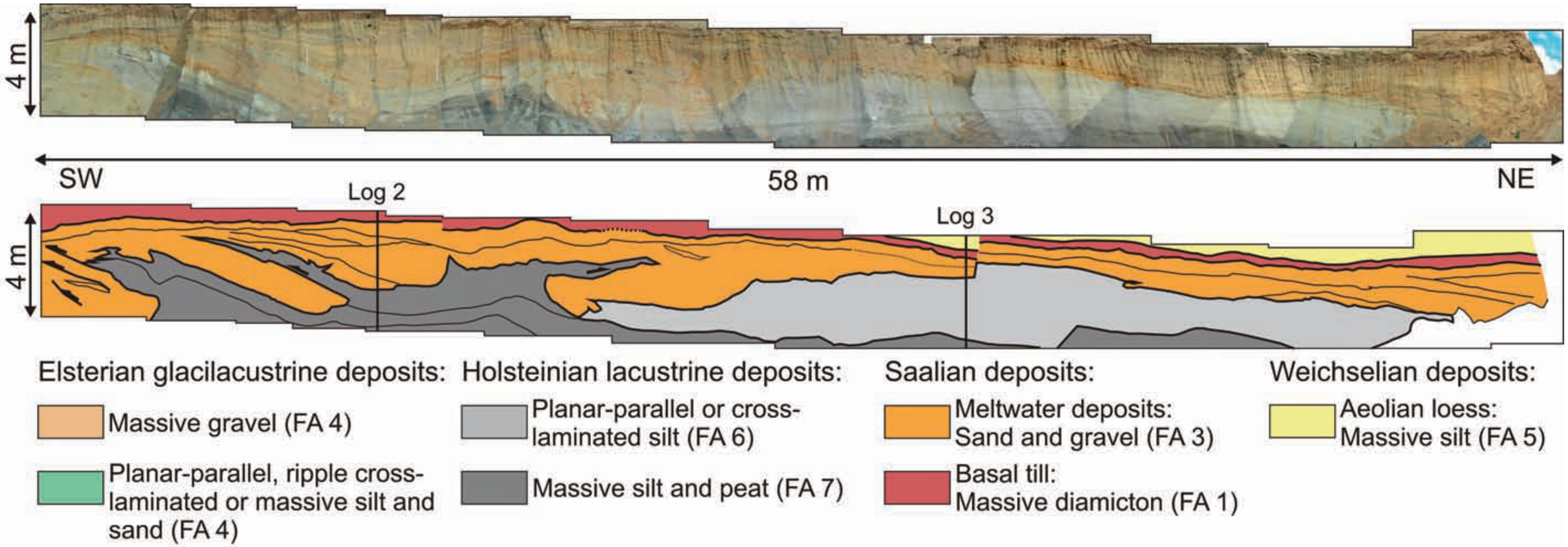

Fig. 9 Photo panel of the outcrop section of »excavation plateau 4«. Saalian meltwater deposits and basal till are overlying Holsteinian interglacial lacustrine deposits. The succession is strongly deformed by mud diapirs, protruding from the interglacial deposits. The photo panel covers the outcrop wall behind logs 2 and 3 (**fig. 2b**). – (May 2009; modified from Lang et al. 2012).

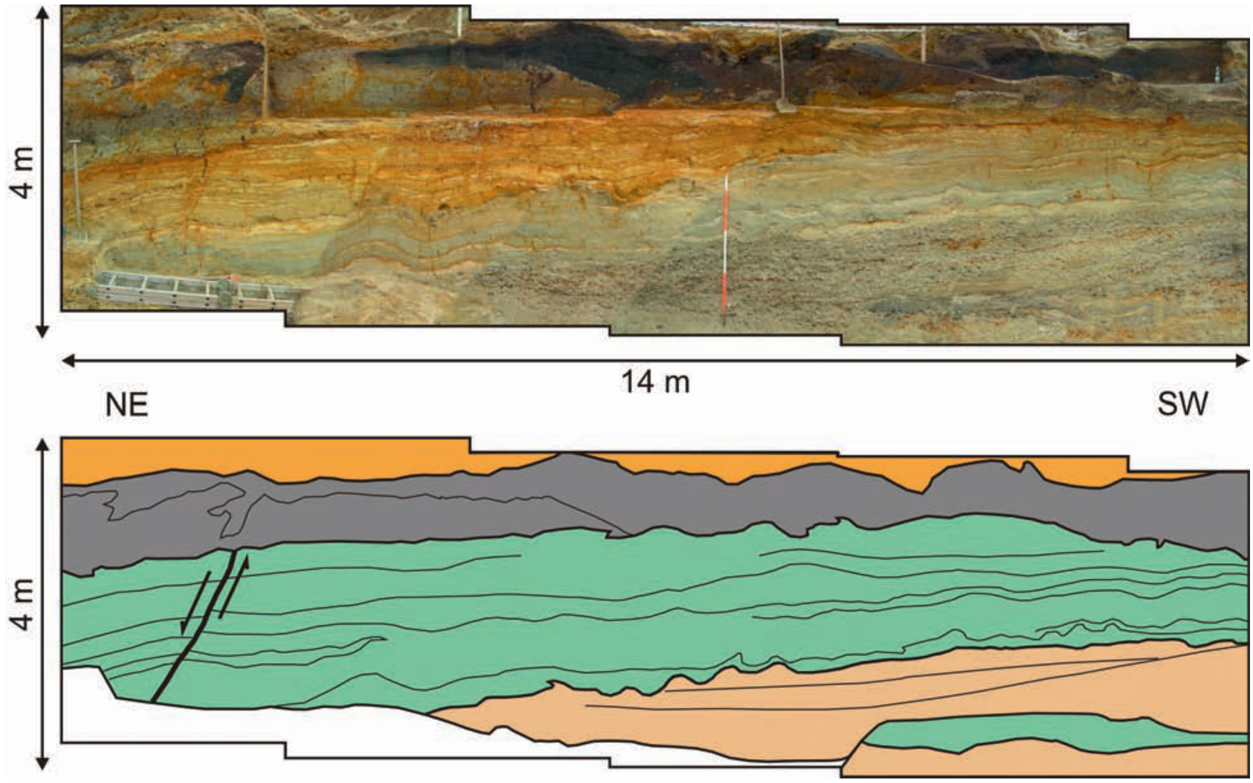

Fig. 10 Photo panel of the outcrop section at the excavation plateau (November 2009). Late Elsterian glacilacustrine gravel, sand and mud are overlain by interglacial mud and peat. For key see **fig. 9**. The photo panel is located immediately southwest of log 1 (**fig. 2b**). – (Photos J. Lang).

Massive, clast-supported gravel lenses or sheets are interpreted as cohensionless sediment gravity flow deposits, partly filling shallow low-sinuosity chutes running down the delta slope (e. g. Postma / Cruickshank 1988; Mulder / Alexander 2001).
The common occurrence of low-energy turbulent flows and suspension fall-out, sediment-gravity flows and ice-rafted debris points to deposition in a glacilacustrine environment (Winsemann et al. 2007).

Aeolian deposits

FA 5: Massive silt

FA 5 consists of yellow to brown, massive silt (F 13). Within the basal part of FA 5, thin layers of fine-grained, massive sand may be intercalated. In some horizons red-brown (iron-rich?) encrustations and roots occur. The thickness of FA 5 ranges from 3 to 5 m. FA 5 has a sheet-like geometry and drapes the pre-existing topography.

Interpretation

The thick, massive beds point to deposition from suspension fall-out. Roots and encrustations point to palaeosoil formation, indicating a terrestrial environment. FA 5 is interpreted as aeolian loess (Miller 1996; Wagner 2011).

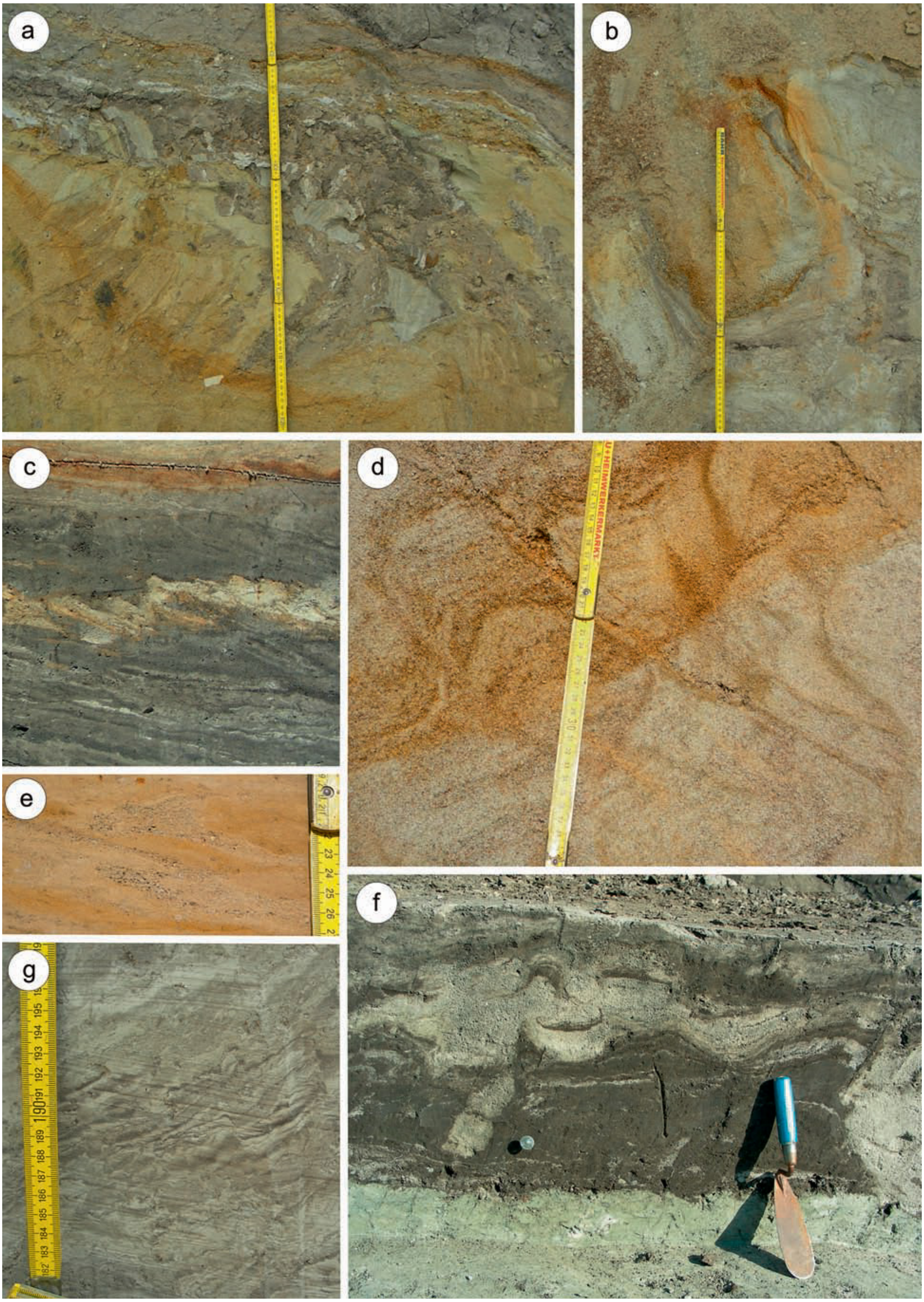

Fig. 11 Deformation structures: **a** reverse faults and folds associated with a diapir (FA 3 and 7). – **b** flame structures intruding into overlying sand and gravel (FA 3 and 7). – **c** sheared sand layer within peat and silt (FA 7), indicating subglacial deformation. – **d** reverse faults with associated fault-propagation folds (FA 3). – **e** sheared sand lenses within basal till (FA 1). – **f** load structures at the contact between sand and silt (FA 7). – **g** normal microfaults and folds within planar-parallel laminated silt (FA 6). – (Photos J. Lang).

Interglacial deposits

Lacustrine deposits

FA 6: Planar-parallel or cross-laminated silt and sand
FA 6 consists of light-grey silt and fine-grained sand with planar-parallel and ripple cross-lamination (F 10; **fig. 8d**). Beds are 5 to 40 cm thick and basal contacts are sharp or erosional and may display load-casts. Plant debris occurs rarely. The succession is deformed by normal faults and folds (**fig. 11g**). Normal faults usually have lengths between 5 to 10 cm and the fault offset is less than 5 cm. Fault planes are planar and dip steeply with 30° to 60° to the NW or SE. Folding affects 5 to 10 cm thick parts of the succession, most folds are developed as recumbent folds with a vergence towards the SE. The upper parts of faults and folds are commonly eroded.
The thickness of FA 6 is 0.5 to 3 m. Deposits of FA 6 have a lens-shaped geometry with erosional basal contacts and a lateral extent of 15 to 35 m, which is modified by diapirism and erosional truncation at the top (**fig. 9**).

Interpretation
Fine-grained, planar-parallel or ripple cross-laminated silt and sand indicate deposition from low-energy, turbulent flows, probably within a lake environment. The absence of peat and larger plant debris is attributed to cold climatic conditions (Urban 2007), leading to enhanced erosion and a higher clastic input. Folds and faults are interpreted as syndepositional slump folds and faults since only thin parts (single beds or parts of beds) of the succession are affected by folding or faulting and their upper parts are commonly eroded by the next flow.
The occurrence of both synsedimentary slump folds and normal faults points to high sedimentation rates (McCarroll / Rijsdijk 2003). Triggers for slump folding were probably failure of oversteepened slopes and liquefaction due to high rates of sedimentation (Mills 1983). Normal faults are related to extensional stress due to rapid sedimentation or oversteepening (Mills 1983). The vergence of normal faults and slump folds points to a south-eastwards directed palaeoslope. The palaeoflow measurements, obtained from cross-lamination, indicate currents from northwesterly directions.
FA 6 is interpreted as interglacial lacustrine deposit. The absence of plant material points to colder climatic conditions at the end of an interglacial.

FA 7: Organic-rich silt and peat
FA 7 consists of brown or black silt (F 11) and peat (F12; **fig. 8c**). Bed thickness is 5 to 40 cm, basal contacts are sharp or deformed by load casts or flame structures. Silt beds are mainly massive. Planar-parallel lamination and ripple cross-lamination are rare. Peat beds are planar-parallel laminated or massive. Bivalves and bivalve fragments (*Anodonta* sp., pers. com., J. Serangeli), plant and wood debris are common. Silt beds and some of the peat beds are carbonate-rich. Beds are gently (5-10°) dipping to the NNE and are strongly deformed by dewatering and load structures. Laterally beds pass downslope from massive peat-silt alternations into massive or laminated silt. At least four fining-upward successions can be observed, passing upwards from organic-rich massive or laminated silt into peat. These successions are separated by erosional surfaces, commonly marked by layers of granules. Deposits downlap onto the underlying deposits (FA 4) and prograde successively towards the northeast.
The thickness of FA 7 is 1 to 4 m (**figs 5-6**). FA 7 is infilling a lens-shaped depression with non-erosional basal contacts. The lateral extent is up to 70 m in northeast-southwest direction and decreases towards the north to 15 m (**fig. 9**).

Interpretation

The massive, fine-grained silt beds indicate deposition from suspension fall-out in a low-energy setting. Rare presence of planar-parallel or ripple cross-laminated beds indicate influence of low-energy turbulent tractional flows. These conditions are commonly met in lakes (Talbot / Allen 1996). The presence of peat and the high content of plant material within the silt indicate warm, interglacial climate conditions (Talbot / Allen 1996, Urban 2007). The occurrence of *Anodonta* sp. is an indicator for a lacustrine environment. The limited lateral extent and thickness of the lacustrine deposits points to deposition within a relatively small, shallow lake. The occurrence of some granule-rich layers and erosional surfaces is attributed to lake-level changes and the shift of the shoreline (Eyles / Eyles 1992; Talbot / Allen 1996). Repeated fining-upward cycles from organic-rich massive or laminated silt into silt and peat are interpreted as shallowing and deepening upwards successions, caused by lake-level fluctuations. The lateral development from SW to NE is interpreted as representing a succession from marginal to deeper lake bottom sediments. The observed shallowing-upward successions resemble those described by Thieme (2005) and Urban (2007) for Schöningen 13II, the site were the throwing spears were discovered.

DEPOSITIONAL MODEL

The Middle Pleistocene succession of Schöningen has been deposited within an Elsterian tunnel valley (Lang et al. 2012). The basal part of the Pleistocene succession comprises meltwater deposits (FA 2) and a basal till (FA 1) of probably Elsterian age (Urban et al. 1988). Elsterian meltwater deposits unconformably overly Palaeogene deposits. The till is up to 10 m thick and pinches-out towards the northeast. The till is unconformably overlain by glacilacustrine gravel, sand and silt. The determined clast composition of meltwater gravel is very similar to the data presented by Tschee (1991) and Elsner (2003) for samples of Elsterian deposits.

The interglacial peat and silt succession (FA 7) was probably deposited during the Holsteinian (MIS 9; Urban et al. 2011). The sedimentary facies points to a shallow lake environment, where organic-rich deposits accumulated within the lake and at the lake margins. Massive silt was deposited by suspension fall-out. Low-energy turbulent flows deposited silt and fine-grained sand during higher water run-off. At the margins of the lake swamps formed and accumulated plant debris. Rising lake-levels caused the preservation of the plant debris, which was subsequently covered by sediment and altered to peat.

The four observed shallowing-upwards successions (**figs 5-6**) resemble those described from the site Schöningen 13II (Cycles I-IV, Thieme 2005). Based on a palynological interpretation, Urban (2007) related the formation of these cycles to changing climatic conditions. Therefore variations of precipitation might have led to lake-level fluctuations and the deposition of shallowing-upward cycles. The peat-rich interglacial deposits are overlain by planar-parallel and ripple cross-laminated silt beds with rare plant debris (FA 6), deposited by low-energy, sediment-laden turbulent flows entering the lake basin. FA 6 resembles the succession of »Cycle V« described by Thieme (2005). The deposition of this succession probably points to increasingly colder climate with less vegetation and higher rates of erosion, which is also recorded in the palynological data (Urban 2007).

During the Saalian Drenthe glaciation coarse-grained sand and gravel were deposited and parts of the interglacial sediments were eroded by these high-energy meltwater flows. Subsequently the meltwater deposits and interglacial deposits became deformed by the advancing glacier. Basal till was deposited on top of the meltwater deposits. The determined clast composition of meltwater gravel is very similar to the

data presented by Tschee (1991) for samples of Saalian deposits. A more comprehensive discussion of the Middle Pleistocene succession, integrating the outcrop data with shear wave seismic reflection and borehole data, is provided by Lang et al. (2012).
The Middle Pleistocene succession is overlain by thick loess deposits of probably Weichselian age (Mania 1995; Urban 1995; Wagner 2011).

DEFORMATION STRUCTURES

The sedimentary succession is strongly deformed, including folds, faults and load structures such as diapirs, flame structures and load casts. Deformation affects the whole succession except the loess at the top of the succession. Glacitectonic deformation in the study area was more intense during the Drenthe glaciation since deformation is much more common beneath and within Saalian deposits than in Elsterian deposits (cf. Elsner 1987).

Diapirs

Large-scale, irregular-shaped wedges intruding from the fine-grained interglacial into the overlying coarse-grained meltwater succession are interpreted as diapirs. Diapirs are the largest structures in the exposed section (**fig. 9**) and are up to 8 m in width and 4 m in height. The surrounding coarse-grained sediment displays strong deformation by reverse faults, folding and brecciation (**fig. 11a**). Reverse faults related to diapirs are dipping to the northeast. Diapirs commonly form as glacitectonic structures (e. g. Schack-Pedersen 2005), but may also occur in non-glaciated settings (e. g. Eissmann 1978; Aber / Ber 2007). The formation of diapirs either is caused by density inversion in unconsolidated sediment (Mills 1983; Aber / Ber 2007) or by freezing and thawing processes in periglacial settings (Eissmann 1978). Density inversion occurs when water-saturated silt or clay is buried beneath coarser-grained, denser sediment, leading to an upward displacement of the overburdened sediment (Mills 1983; Aber / Ber 2007). This process may be amplified by the additional load and increased pore pressure provided by an advancing glacier (McCarroll / Rijsdijk 2003; Aber / Ber 2007). Thrust fault deformation in front of an advancing glacier may trigger the mobilization of liquefied mud (Schack-Pedersen 2005). In periglacial permafrost settings, freezing and thawing of interstitial water in unconsolidated sediment causes changes in volume and diapirism (Eissmann 1978). The sheared upper parts of the diapirs and the development of subparallel reverse faults is an indicator of ice-marginal deformation by ice-thrusting (Eissmann 1987; McCarroll / Rijsdijk 2003). Sheared tops of diapirs and reverse faults dip to the northeast and are southwest vergent, in accordance with an ice advance from the northeast.

Flame structures

Small-scale flame-shaped wedges of sediment intruding into the overlying bed are interpreted as flame structures. Flame structures are usually 10 to 20 cm long and intrude into the overlying sediment (**fig. 11b**). The flame structures may be aligned vertically or subhorizontally. Flame structures are dewatering structures caused by loading (Mills 1983). Subhorizontally aligned flame structures are attributed to subglacial deformation (Aber / Ber 2007).

Load structures

Ball-shaped or irregularly shaped features protruding into the underlying bed (**fig. 11f**) are interpreted as load structures. Load structures are 10 cm to 1.2 m wide and are both recorded from the fine-grained succession and the contact between the basal silt unit and the overlying sand and gravel unit. Loading occurs if water-saturated mud is rapidly overlain by more dense sediment, which sags into the underlying bed (Mills 1983). In front of the advancing glacier additional load may be applied, enhancing the formation of load and dewatering structures (McCarroll / Rijsdijk 2003).

Folds

Folding occurs in the interglacial and Saalian deposits. Folds are asymmetric and have wavelengths of 0.2 to 2 m. Some folds are developed as recumbent folds. Folds accompanying reverse faults are interpreted as fault-propagation folds (**fig. 11d**). The intrusion of diapirs also causes folding of the surrounding sediment.

Reverse faults

Reverse faulting occurs within the Elsterian and Saalian meltwater deposits (**fig. 11a. d**). The faults can be traced for up to 3 m. Fault offset is 10 to 50 cm. Fault planes are planar and dip steeply with 20 to 40° towards the northeast. The vergence of reverse faults is an indicator for the direction of ice advance (Aber / Ber 2007). Within the Drenthe meltwater deposits, reverse faults occur in association with diapirs. The southwest vergence of the reverse faults and diapirs indicates an ice advance from the northeast.

Ductile deformation structures

Ductile deformation includes recumbent folds, boudinage and deformed flame structures (**fig. 11b-c. e**). These structures are indicative for subglacial deformation (McCarroll / Rijsdijk 2003).

DISCUSSION AND CONCLUSIONS

The studied outcrop section at Schöningen 12II DB exposes a Middle to Late Pleistocene succession, comprising Elsterian, Holsteinian, Saalian and Weichselian deposits.

During the Elsterian glaciation, meltwater deposits and basal till were deposited. These deposits were only preserved in the southwestern (lower) part of the basin and were subsequently overlain by fine-grained glacilacustrine deposits. The reconstruction of the large-scale depositional architecture from borehole and shear wave seismic data reveals the presence of an Elsterian tunnel valley, providing the accommodation space for the Middle Pleistocene succession (Lang et al. 2012)

Deposition during the Holsteinian interglacial (MIS 9) took place within a small, shallow lake. The basal lake deposits consist of peat and silt alternations, which can be subdivided into four shallowing-upward successions. These shallowing-upward successions are interpreted as representing lake-level fluctuations caused by changes in precipitation and surface run-off, probably related to climatic variations. Mania (1995) interpreted this lake as fill of an abandoned fluvial channel. However, the absence of fluvial deposits and the large extent (15-70 m width; **figs 9-10**) of the succession point to deposition within an elongated lake basin. At the transition from interglacial to glacial climate plant growth ceased and planar-parallel or ripple cross-laminated silt was deposited from turbulent flows entering the lake. Palaeoflows were from northwesterly directions, suggesting that topography was similar to the recent topography. The seismic image of the Holsteinian succession reveals laterally and vertically stacked delta systems, which were deposited on the western margin of the interglacial lake. Repeated lake-level changes controlled the deltaic deposition and thus the formation and distribution of the archaeological sites (Lang et al. 2012).

During the Saalian Drenthe glaciation, the succession was unconformably overlain by coarse-grained meltwater deposits and basal till. Main palaeoflow directions were from the northeast. During the subsequent glacier advance the Holsteinian lacustrine and Drenthe meltwater successions were strongly deformed, including the formation of diapirs, reverse faults and folds. These deformation structures indicate an ice advance from the northeast, corresponding to the palaeoflow direction obtained from the meltwater deposits.

Regarding the interglacial succession the following conclusions can be drawn:

– The Middle Pleistocene interglacial deposits of Schöningen have been deposited in a small, elongate lake basin, which formed in a remnant Elsterian tunnel valley (Lang et al. 2012). There is no evidence for fluvial channels. The facies associations and stacking patterns suggest that this lake was affected by repeated lake-level fluctuations, leading to the deposition of climatically controlled shallowing-upward sequences.
– These interglacial shallowing-upwards successions at Schöningen 12II DB can probably be correlated with the interglacial succession at Schöningen 13II.

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ZUSAMMENFASSUNG / ABSTRACT

Der Aufschluss 12II DB im Tagebau Schöningen: Sedimentäre Fazies und Faziesarchitektur

In diesem Artikel dokumentieren wir die stratigraphische Entwicklung und interne Faziesarchitektur der mittel- bis spätpleistozänen Abfolge im Bereich des DB-Pfeilers (Schöningen 12II DB) im Tagebau Schöningen. Wir schlagen ein neues Ablagerungsmodell vor, das eine Analyse der sedimentären Fazies, der Ablagerungsprozesse und der Faziesarchitektur umfasst. Während der Elstervereisung wurden Schmelzwasserablagerungen und Grundmoräne in einer subglazialen Rinne (»tunnel valley«) abgelagert. Holsteinzeitliche Ablagerungen wurden in einem kleinen, flachen See abgelagert, der sich in den Resten der subglazialen Rinne bildete. Die basalen Ablagerungen dieses Sees bestehen aus einer Schluff-Torf-Wechselfolge, die in vier Verlandungsfolgen unterteilt werden kann. Diese Abfolgen werden als Überlieferung von Seespiegelschwankungen interpretiert, die vermutlich klimatisch gesteuert durch Schwankungen der Niederschlagsmenge und des Oberflächenabflusses verursacht wurden. Am Übergang vom Interglazial zum Glazial ging die Vegetation zurück und turbulente Strömungen transportierten Schluff und Feinsand in den See. Die Strömungen kamen von Nordwesten, was eine Paläotopographie ähnlich der heutigen Topographie vermuten lässt. Während der saalezeitlichen Drenthevereisung wurde die Abfolge diskordant durch grobkörnige Schmelzwasserablagerungen und Grundmoräne überlagert. Die generelle Paläoströmungsrichtung war aus Nordosten. Während des anschließenden Eisvorstoßes wurden die holstein- und saalezeitlichen Ablagerungen stark deformiert und es kam zur Bildung von Diapiren, Aufschiebungen und Falten. Die Deformationsstrukturen weisen auf einen Eisvorstoß von Nordosten hin, was zu der ermittelten Paläoströmungsrichtung passt. Die mittelpleistozänen Ablagerungen sind mit vermutlich weichselzeitlichem Löss bedeckt.

The 12II DB outcrop section at Schöningen: sedimentary facies and depositional architecture

In this paper we document the stratigraphic evolution and internal facies architecture of the Middle to Upper Pleistocene sedimentary succession, exposed at Schöningen 12II DB in the Schöningen open-cast mine. A new depositional model including sedimentary facies, depositional processes and depositional architecture is proposed. During the Elsterian glaciation a tunnel valley was incised beneath the ice sheet and meltwater deposits and basal till were deposited. Deposition during the Holsteinian interglacial (MIS 9) took place within a small shallow lake, which formed within the remnant tunnel valley. The basal lake deposits consist of peat and silt alternations, which can be subdivided into four shallowing-upward successions. These successions are interpreted as representing lake-level fluctuations caused by changes in precipitation and surface run-off, probably related to climatic variations. At the transition from interglacial to glacial climate plant growth ceased and silt and fine-grained sand were deposited from turbulent flows entering the lake. Palaeoflows were from northwesterly directions, suggesting that topography was similar to the recent topography. During the Late Saalian Drenthe glaciation, the succession was unconformably overlain by coarse-grained meltwater deposits and a basal till. Main palaeoflow directions were from the northeast. During the subsequent glacier advance the Holsteinian and Saalian successions were strongly deformed, including the formation of diapirs, reverse faults and folds. These deformation structures indicate an ice advance from the northeast, corresponding with the palaeoflow direction obtained from the meltwater deposits. The Middle Pleistocene deposits are covered by loess of probably Weichselian age.