Lake deposits of the Early Triassic Buntsandstein in Central Germany: Type localities of oolites and stromatolites.

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Introduction

The Central European Basin (also Germanic Basin) is the type locality of the Triassic. Here, the system was named and defined as a stratigraphic unit by ALBERTI in the year 1834. The given name is based on the tripartite succession of Buntsandstein, Muschelkalk and Keuper (today supergroup of the Germanic Triassic), which covers wide areas of southern and central Germany. The Buntsandstein group consists mostly of fluvial, aeolian and lacustrine sediments, deposited in terrigeneous environments. Only the Upper Buntsandstein of the eastern and central basin is partly characterised by restricted shallow-marine to Sabkha environments. The Muschelkalk group was deposited during several marine ingressions from the Tethyan sea. Most sediments of the Muschelkalk group are represented by shallow marine limestones (ramp carbonates) and evaporites. The Keuper group comprises most of the Triassic time scale and shows a broad variety of terrigeneous and marine environments. As a whole, the supergroup of the Germanic Triassic represents one of the major continental basins during the Triassic, situated near the centre of Pangea but close to the Tethyan sea (fig. 1).

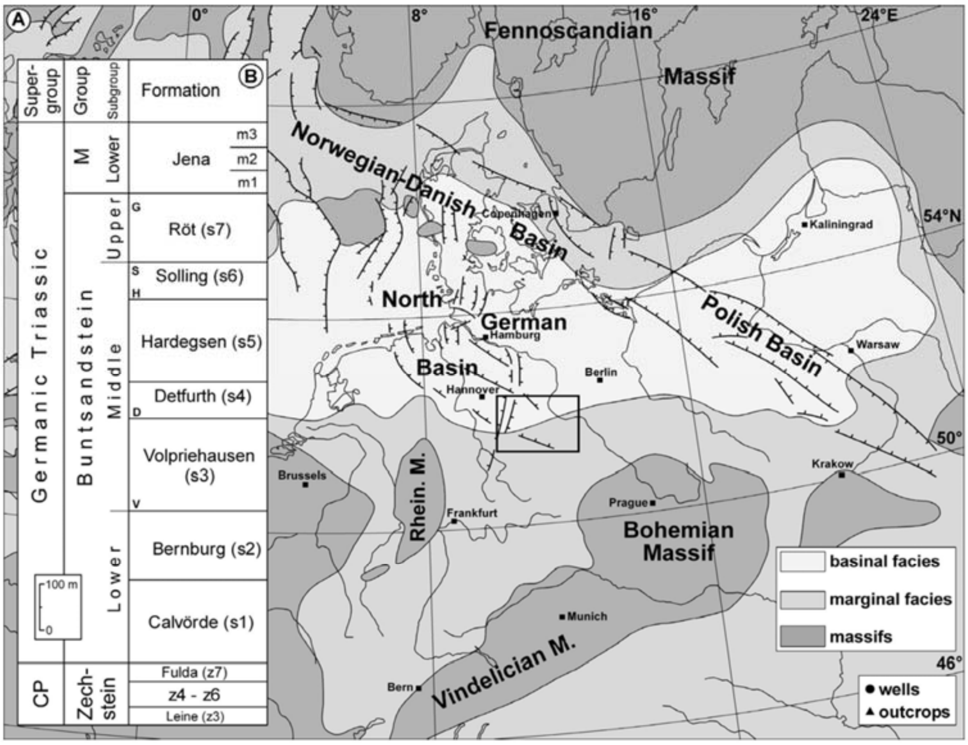


Fig. 1: Early Triassic paleogeography of the Central European basin and stratigraphy of the Buntsandstein group (BACHMANN et al. 2009)

The position of the basin between 20 and 30° latitude caused an arid climate, probably strongly modified by an intensive monsoon (e.g. PARRISH 1993). Some features of the basin-fill make the Germanic Triassic interesting for sedimentological studies. Especially the huge extension (500 x 1000 km) of cyclic mudflat deposits in the Buntsandstein and Keuper groups are difficult to explain from a sedimentological point of view, because transport of sediments in such a flat basin can not be compared with recent mudflats which show only limited extent. But major problems arise also from the very uniform facies and thickness trends of Muschelkalk and Buntsandstein deposits (“layercake geometry”) for reconstructions of the sedimentary environments and are subject of intensive discussion. Some of these questions will be addressed during this excursion. The Triassic of the Germanic Basin is also interesting concerning evolution and preservation of life. Some continental series of the Buntsandstein, although deposited in lakes or rivers, contain neither fossils (like plant remains, molluscs or vertebrates) nor other traces of life like bioturbation or rootlet beds. Ostracods and chonchostracans are the only exception, thus providing the base of biostratigraphy (KOZUR & SEIDEL 1983). Plants, bivalves, gastropods and reptiles re-appear in the Middle Buntsandstein but remain rare. It could be assumed that the extinction event at the Permian-Triassic boundary affected the fauna for some million years (WEIDLICH 2007) or, alternatively that strong fluctuations of environmental conditions prevented the establishment of a permanent fauna (PAUL 2010). The abundance of stromatolites and giant oolites in fresh water deposits points to sedimentation very similar to Precambrian lakes, most probably caused by the lack in cyanobacteria-consuming biota (WEIDLICH 2007).

Especially the Lower Buntsandstein is characterized by deposits of a large shallow fresh-water to brackish lake which occupied the basin centre of the Central European Basin. But, also the Middle Buntsandstein, which is in general coarser and contains more fluvial deposits, shows a broad variety of lacustrine sediments, deposited either in temporary lakes at the floodplain or in bigger endorheic, partly restricted lakes in the basin centre. Acritarchs, which were found in the eastern Basin (Poland), indicate even limited access to the sea (BECKER 2005).

The focus of the excursion is on the Lower Buntsandstein lake. Some typical outcrops are visited, where KALKOWSKY (1903) firstly described and defined stromatolites, and where BRÜCKMANN (1721) used the term "Oolithi" for the first time. Famous outcrops of near-shore to pelagic lacustrine deposits are supplemented by deep well core material of a younger Middle Buntsandstein lake.

The Buntsandstein of the Central European basin

Paleogeography

During the late Permian, the Central European basin was several times flooded by the Arctic ocean via a graben system within the future North Sea area. Sea-level changes and hyperarid climate led to the deposition of thick evaporites. Step by step, the basin was filled up with salt and close to the Permian-Triassic boundary, when accommodation space was exhausted, a large salt pan (inland-sabkha) with low sedimentation rates extended over most of central Europe. At the basin margins, slowly growing alluvial fans developed which gradually passed to salty mudflats (HUG 2004). These mudflats are characterized by structureless sandy mudstones (“Bröckelschiefer”) and occupied a belt more than 100 km wide. Climate change to more precipitation and uplift of the hinterland caused the transition to fluvial and aeolian deposition close to the Permian-Triassic boundary. This boundary was fixed in several boreholes and outcrops on the base of magnetostratigraphy, but is devoid of fossils. The basin was closed, so that an endorheic lake evolved in the subsiding centre of the basin (fig. 1). Basin margins were fringed by short alluvial fans merging to braid plains of ephemeral streams. Deposits of the early Buntsandstein rivers cover most of southern Germany. A north-directed fluvial trunk system left behind rather uniform deposits of cross-bedded sandstones. The homogeneous facies of stacked braided river sediments and inreased thickness in a N-S striking area of increased subsidence (Hessian sub-basin) indicate the persistence of this fluvial transport sytem.

The facies of central and northern Germany is much more diversified: The more distal parts of the sand plains were occupied by aeolian dunes and small seasonal lakes (MAAß et al. 2011). The margins of the main lake are characterized by a broad variety of beach- and shoreface sands, deltas and mud flat deposits (VOIGT & GAUPP 2000, FENSTERER & VOIGT 2010). Further to the basin centre, ooid-shoals evolved and where mixed with the sands transported from the south. Strong fluctuations of the shoreline are expressed in rapid vertical and lateral facies changes. A similar facies transition is expressed in the Polish part of the basin and in the Netherlands (PALERMO et al. 2008).

Both deposits of the central lake and fluvial sediments of the basin margins often show a characteristic cyclicity (e.g. SCHULZE 1969, GELUK & RÖHLING 1997), which was recently attributed to base-level changes by different authors (e.g. BECKER 2005, PALERMO et al. 2008). GELUK & RÖHLING 1997 and MENNING et al. 2005 postulated orbital cycles as a driving force for the observed cyclicity. Especially the eccentricity with a periodicity of 100.000 years is believed to be the main control of the solar-induced cycles expressed in the succession. In this model, precipitation intensity triggered river discharge and evaporation and thus has controlled the amount of river load and lake level fluctuations.

The Buntsandstein was deposited in an epicontinental sag basin of moderate subsidence within the land mass of Pangea. The cycles can be correlated over vast areas as it was proven by GELUK & RÖHLING (1999) and BECKER (2005). Thickness changes and some synsedimentary shallow unconformities are attributed to mild tectonics (intraplate stresses) and initial diapirism of Zechstein salt. The main structures within the basin are two N-S striking areas with reduced subsidence: The Eichsfeld-Altmark swell (HERRMANN 1956, PAUL & KLARR 1987, RÖHLING 1991, PAUL 1993) in the central basin and the Hunte swell in the western basin (TRUSHEIM 1961, WOLBURG 1962). As most of the clastic material was trapped in the adjacent subbasins, these swell areas were the preferred places for oolite and stromatolite formation during the Early Triassic (PAUL 1982).

Stratigraphy of the Buntsandstein group

The early Triassic Buntsandstein group of Germany is bounded by the Upper Permian Zechstein group, mainly composed of evaporites and the overlying Muschelkalk group of marine limestones. The Buntsandstein group is divided into three subgroups, characterized by predominantly lacustrine deposits and fine-grained fluvial deposits in the Lower Buntsandstein, fluvial deposits of the Middle Buntsandstein and a fluvial to marine-evaporitic succession of the Upper Buntsandstein (fig. 2). The thickness of the Buntsandstein group increases from a few hundred metres of the fluvially dominated succession of southern Germany to more than 1300 m in the Hessian trough and more than 1500 m in the Glückstadtgraben close to the North sea basin.

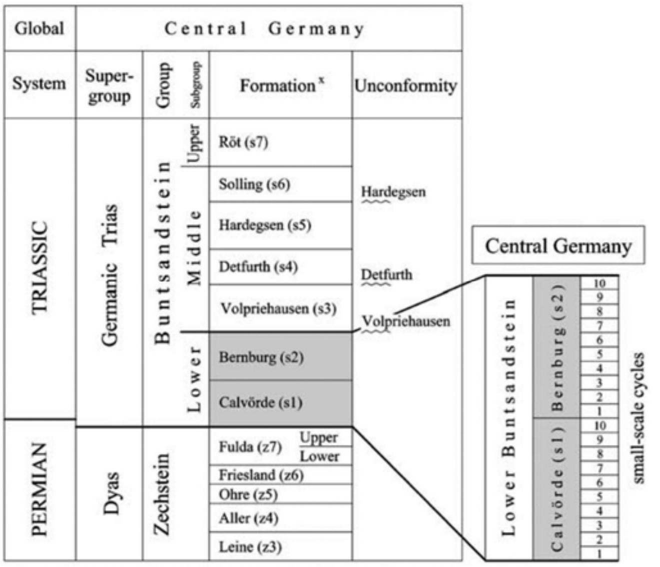


Fig. 2: Lithostratigraphy of the Lower Buntsandstein. The Lower Buntsandstein is subdivided in two formations each comprising ten fining upward cycles, traceable throughout the basin (Szurlies 2003).

The Lower Buntsandstein

The Lower Buntsandstein is divided into two lithostratigraphic units: Calvörde and Bernburg formations (Fig. 2). Both of them contain several clayey-upward cycles; the Calvörde Formation consists of ten fining-upward cycles, whereas in the Bernburg Formation up to 14 cycles can be observed in the basin center. Towards the margins and internal swells the uppermost cycles are often missing due to erosion beneath the overlying Volpriehausen Formation (Volpriehausen unconformity) of the Middle Buntsandstein. The fining-upward cycles can easily be recognised in the γ-ray logs. In the basin centre, the base of the Bernburg formation is traditionally placed at a major oolite bed; the “Hauptrogensteinzone”, but detailed investigations of Schüler (1976), Paul & Klarr (1987) and Röhling (1993) proved that the maximum deposition of ooids was not contemporaneous through the basin. So, the main oolite bed occurs at the base of the 1th cycle of the Bernburg Formation in the eastern basin, while 50 km apart, in Lower Saxony, maximum thickness of oolites occurs in the 2th and 3rd cycle (fig. 3).

Biostratigraphic subdivision is based on conchostracans. Seidel & Kozur (1983), Kozur 1999 established a biostratigraphic scale for the Buntsandstein of 10 assemblage zones. Some of the conchostracans occur also in other places, thus allowing the correlation with the international scale (Kozur 1999, Kozur & Bachmann 2008). Szurlies (1999, 2003) was able to date the Buntsandstein throughout the basin on the base of magnetostratigraphy. This correlation confirmed biostratigraphic data and also the precision of basin-wide lithostratigraphic correlation (fig. 4). On the base of the combined data-set, it was concluded that the observed cyclicity represents basin-wide simultaneous changes of deposition (Szurlies et al. 2003). Nevertheless, formation of oolites occurs at shoals of limited extent and formation of beds traceable over hundreds of kilometres requires migration of facies belts, as does the covering of a fluvial sand plain with river deposits. This would suggest that migration of facies belts occurred faster than precision of stratigraphic dating.

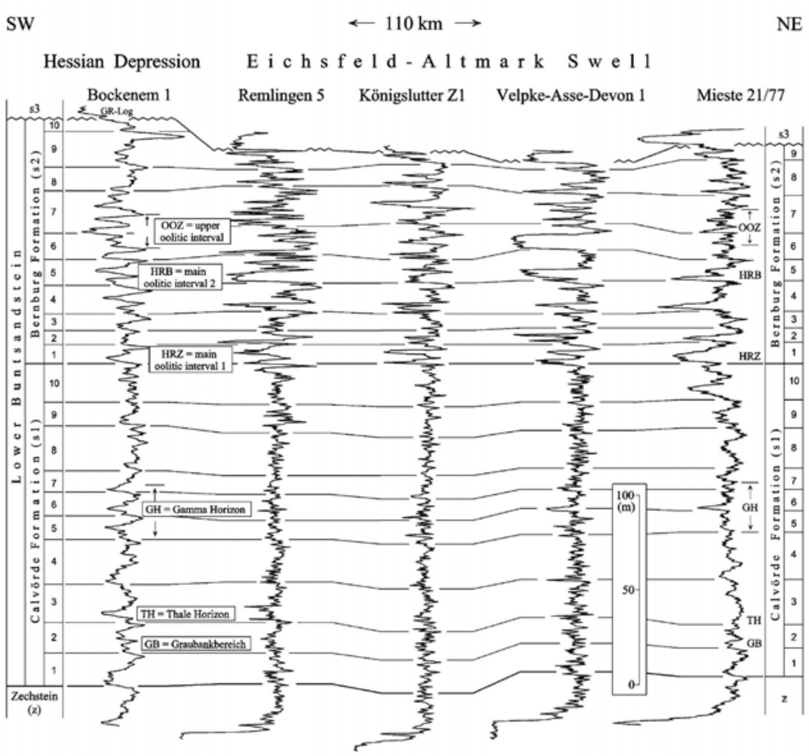


Fig. 3: Correlation of Lower Buntsandstein cycles across the Eichsfeld-Altmark swell shows a sharp boundary between the clay- and sand-dominated Calvörde Formation and the oolite-rich Bernburg Formation (SZURLIES 2003). Individual cycles of the Calvörde formation are better defined east and west of the paleohigh.

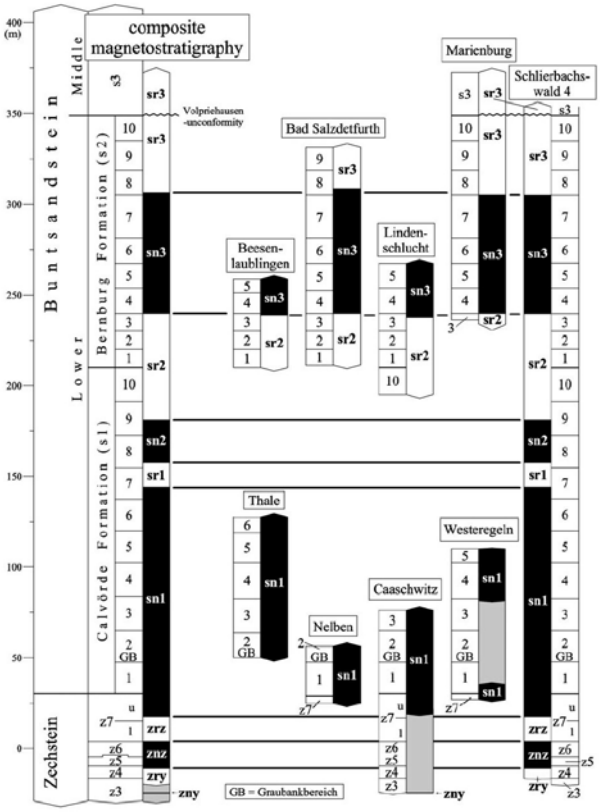


Fig. 4: Composite magnetostratigraphy of the Lower Buntsandstein in the Central European basin. Note that lithostratigraphic boundaries seem to be isochronous in different sections (SZURLIES 2003).

Depositional model of the Lower Buntsandstein

On the base of boreholes and surface outcrops, VOIGT & GAUPP (2001) established a simple sedimentary model for the deposition of sandstones, oolites and claystones in the south-eastern basin (fig. 5), which was affirmed and refined for the Netherlands by Palermo et al. (2008), see fig. 6).

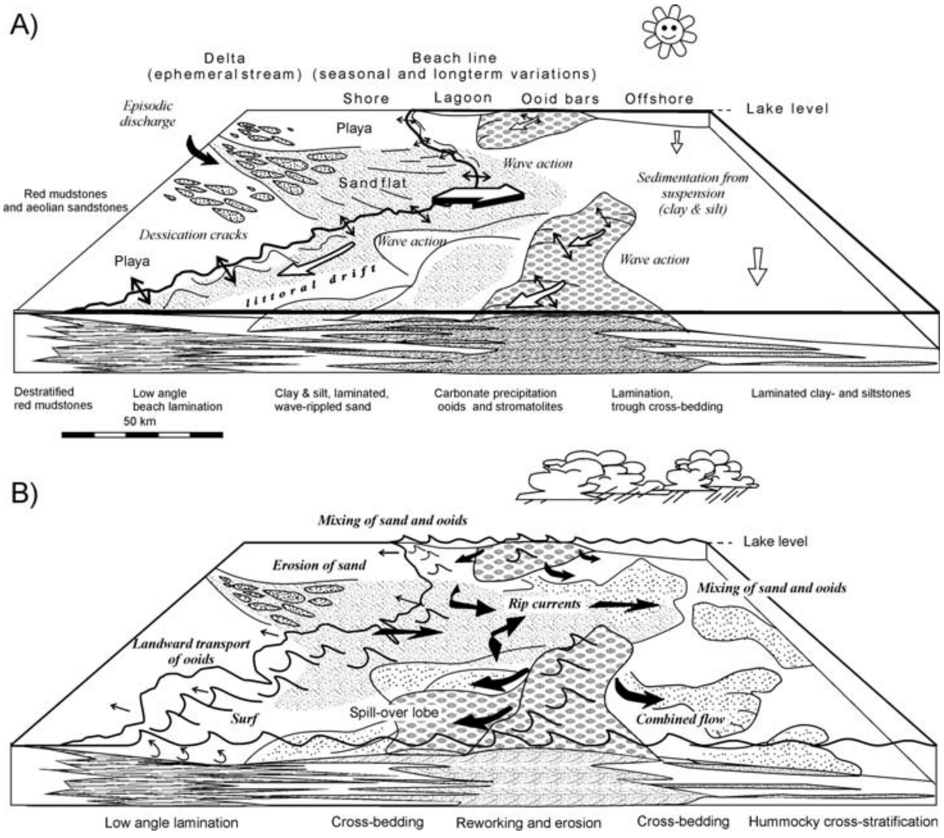


Fig. 5: Depositional model of the Early Buntsandstein lake margin (modified from VOIGT & GAUPP 2000). A) During fair weather conditions, ooids were produced at detached shoals, clastic input occurred from rivers entering the lake from the southern basin margin. B) During stormy weather, ooids were transported into deeper basin parts and mixed with sand.

Both models presuppose that the formation of oolites requires the absence of terrigeneous input and assume formation of shallow oolite bars (shoals) offshore. Wide distribution of the pure oolite facies was induced by the migration of shoals according to changing lake level or by autocyclic processes (exhaustion of depositional space by ooid formation). The widespread mixed facies of sandy oolites was attributed to spill-over lobes as a result of storm redeposition. The model of VOIGT & GAUPP (2001) was created only for times when deposition of ooids occurred. PALERMO et al. (2008) considered that the oolite horizons are traceable over hundreds of kilometres and are always separated by thick units of clay and sand without any ooids, indicating, that formation of ooid shoals was limited to certain conditions. So, a second model for lake-level lowstands was developed. Destratified clay- and siltstones with abundant anhydrite nodules and roots are considered as desiccated mudflats which spread over older lake deposits. The remaining lake in the basin centre was characterized by enhanced terrigeneous input and thus carbonate precipitation declined.

The interpretation of sands replacing the ooid shoals in some cycles is different in both models: while Voigt & Gaupp (2001) assume a delta-like depositional system connected to the rivers flowing into the lake, Palermo et al. (2008) suggested the formation of flat isolated sand shoals off the coast as a substitute of oolite bars.

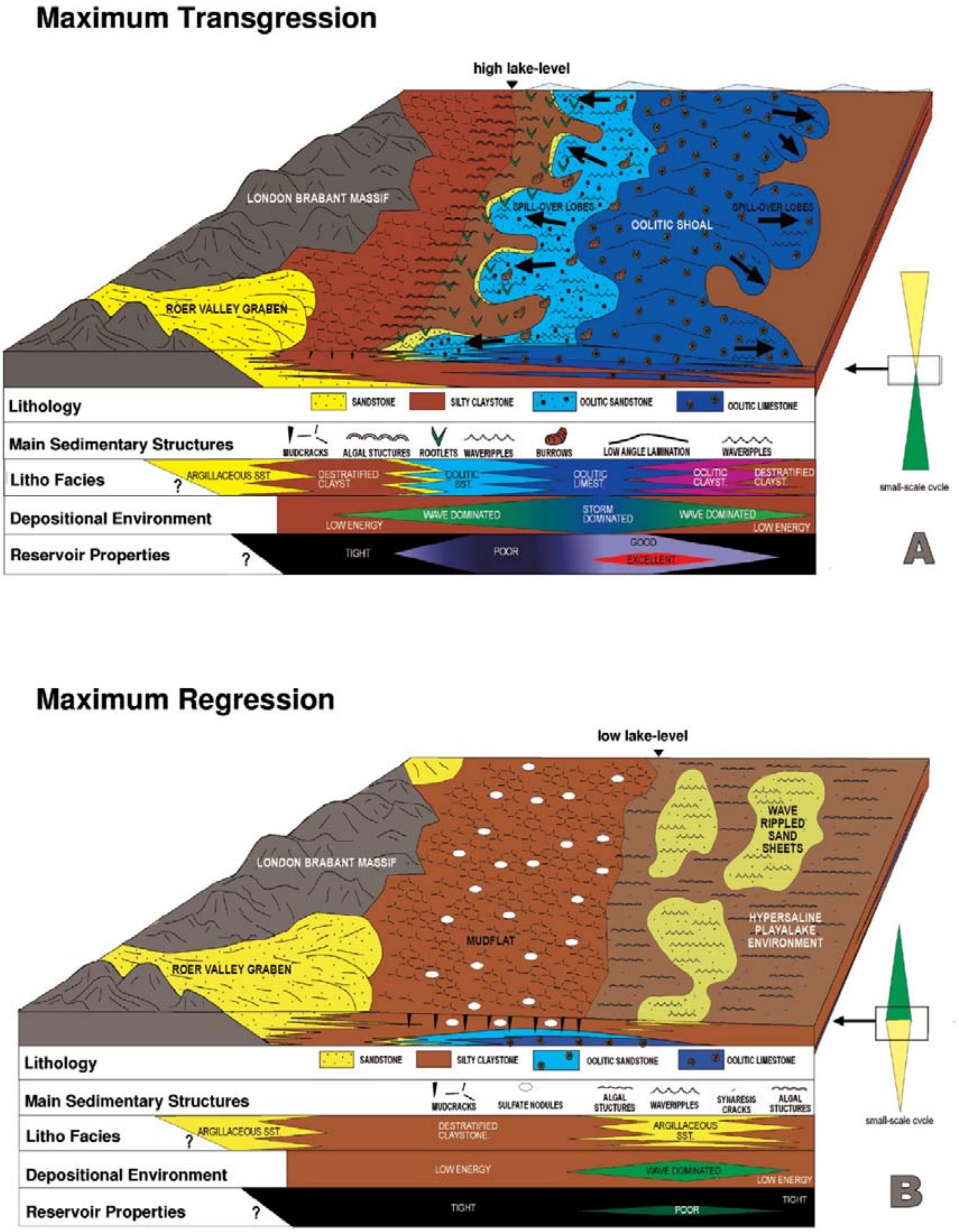


Fig. 6: Refined depositional model of Palermo et al. (2008): Oolite deposition during transgressive phases was followed by a breakdown of the carbonate factory due to enhanced terrigeneous input. Extended mudflats formed during periods of low precipitation. Ooid shoals were replaced by sand shoals.

The Middle Buntsandstein

The Middle Buntsandstein is divided into four formations: Volpriehausen, Detfurth, Hardegsen and Solling formations, each starting with a basal sandstone or conglomerate, tens of metres thick, which passes gradually in a succession of claystones and sandstones. Most of the basal sandstones are of fluvial or aeolian origin. The sandstone-claystone successions are interpreted to represent the same depositional system. While basin margin deposits consist of stacked braided river channels, the amount of flood-plains fines increases continuously towards the central basin. Falling base-level resulted in river incision and ended finally with formation of peneplains and a disconformity close to the basin margin. Slowly increasing base-level led to channel-dominated successions due to frequent erosion of inter-channel facies (e.g. BECKER 2005). A rapid rise of base-level supported preservation of floodplain deposits and caused the observed clay and silt-rich deposits in the upper parts of formations.

According to the position of the excursion area close to the basin centre, deposits of the Middle Buntsandstein in the excursion area contain therefore also units which were deposited on flood plains. Floodplains are topographically lower than river levees and so temporary shallow lakes could develop after floods. Although the Middle Buntsandstein of Poland contains also oolitic horizons and point to a similar endorheic lake system like in the German Lower Buntsandstein (BECKER 2005), most lake deposits of the excursion area are characterised by these flood-plain lakes. Typically, they are represented by red claystones with some sandstone intercalations, often rippled or bioturbated.

Additionally, grey to greygreen, and dark grey coloured units are intercalated in the predominantly red sandstone units in the Middle Buntsandstein succession of the Central European basin and the adjacent Hessian Subbasin. They occur especially in the Volpriehausen and Solling formations. Typical thickness of these clay- and siltstones with a varying content of thin (mm to few cm) sandstone layers is between 5-20 m. Lateral extension of these units varies strongly according to stratigraphic position. Some of these lacustrine horizons occupied much of the whole Lower Saxony (about 48,000 km^2). As these clay-dominated horizons have a natural high γ-radiation, they provide good regional markers in the γ-ray logs. Some of the claystones contain high amounts of uranium, arsenic and heavy metals like lead, copper and zinc, leading in the sixties to some exploration efforts.

The deposits are interpreted to be deposited in shallow, in maximum some tens of metres deep lakes with stable stratification of the water column. Reducing conditions are reflected by the high metal contents and the good preservation of plant debris. Both lake types will be presented during this excursion: Red claystones of a small flood-plain lake are exposed at the base of the Middle Buntsandstein in Großwangen (stop 5); core material of an extended perennial lake of the Solling formation will be shown and discussed in Königslutter (stop 4).

Sedimentology of Buntsandstein oolites

The oolites of the Lower Buntsandstein of Germany were investigated by KALKOWSKY (1908), VOSS (1928), DORN (1953), USDOWSKI (1963), RICHTER (1983) and PAUL et al (2011). Ooids occur both in pure oolitic limestones as in a varying mixture with quartz sand. They form single layers of some centimetres thickness or up to ten metres thick units. These packages are intercalated in red sandy claystones which make up more than 50% of the whole lake succession. Oolitic limestones are limited to the central basin and are most abundant in a broad belt, some tens of kilometres off the lake's shore line.

Ooids have normally small cores consisting of quartz-grains, mica or ostracod shells. Size varies strongly; Diameters of 0.2 to 3.5 mm are most abundant, but sizes up to 12 mm are not uncommon in some regions (stop 3). Richter (1983) concluded a primary composition of high-Mg calcite, because he observed randomly distributed idioblastic dolomite crystals in the calcitic ooids. Primary structures of the ooids are seldom preserved; often they are recrystallised or even dolomitised. Both concentric layers of calcite and radial orientation of calcite crystals across the whole ooid occur. Outer layers of the biggest ooids have an irregular structure close to the observed crinkly surface of stromatolitic crusts. In thin-sections, the coatings of such ooids consist of columnar stacked dark and light laminae divided by deep furrows. The outer surface of these "cerebroid" ooids (Carozzi 1962) is very similar to blackberries. Paul & Peryt (2000) assume quick precipitation, probably under the influence of cyanobacteria. Some of these spherical carbonate grains can be classified as oncoids.

Sedimentology of Buntsandstein stromatolites

Dome-like structures in the succession of the Lower Buntsandstein of northern Germany were first described and named as stromatolites and stromatoids by Kalkowsky (1908) who also already assumed a biogenic origin of these structures. Further investigations of the stromatolites from the type locality go back to Peryt (1975), Paul & Peryt (2000) and Paul et al. (2011).

The stromatolites are distributed in a limited area close to the basin centre and in the surroundings of the Eichsfeld swell (fig. 7).

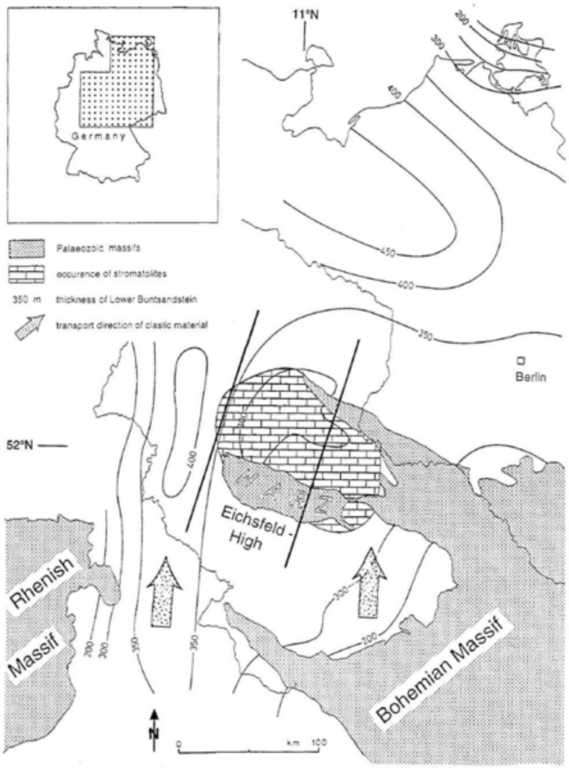


Fig. 7: Occurrence of stromatolites in the Lower Buntsandstein of the central basin is restricted to an intrabasinal paleohigh, the Eichsfeld swell (PAUL 1982). Oolitic limestones reach their highest thickness in the same area, which is explained to be the result of clastic sediment trapping in the surrounding lows. The uplift of Palaeozoic massifs occurred after deposition of the Lower Buntsandstein, during Late Cretaceous.

They are always closely associated with oolites. Often they start as thin algal mats on top of rippled oolite beds or start to grow on giant cerebroid ooids. In large outcrops (stop 3), it can be observed that single oolite beds are covered by closely spaced domal stromatolites of the same size. They form horizons traceable over more than 700 m (PAUL et al. 2011). Domal growth forms prevail, but stromatolitic crusts and centimetre-high branching columns also occur. Input of terrigeneous material, mostly clay, terminated stromatolite growth, while shedding of ooids interrupted it only temporary (PAUL & PERYT 2000). This proves, that migrating ooid bars and ooid ripples co-existed with stromatolites. Internal structure is characterised by various growth structures of and interstices, filled with quartz, ooids and broken stromatolitic crusts. Internal growth structures were described by PAUL & PERYT (2000). They distinguished between domal/laminar – and columnar/digital forms. Microstructures were differentiated by the same authors as spongy-fenestrate and fan-like fabrics. Organic material is not preserved; diagenesis was accompanied by strong recrystallisation. According to the considerable size of stromatolites and the strong relationship to oolites, PAUL et al. (2011) compare the depositional system with recent alkaline lake deposits in eastern Africa and the marginal marine stromatolites of the Shark bay, Western Australia. They conclude a subtidal environment of an alkaline lake, protected from terrigenous input.

Excursion

Stop 1: Clay pit Beesenlaublingen.

Location: The large (700 x 300 m) abandoned clay pit is situated between the river Saale and the regional road B6 near between the small towns of Alsleben and Könnern. It can be reached easily from the highway BAB 14, exit Plötzkau. The best way to enter the large pit is to follow the Saale-bicyclepath stream-up from the village of Zweihausen.

Coordinates of the pit centre: 51°41’48’’N, 11°42’16’’E

Geological setting: North of the Harz mountains, mesozoic rocks reach a wide extension, especially Triassic and Cretaceous formations occupy large areas. The area between the two basement-uplifts of the Harz and the Flechtingen High is called the Subhercynian basin, although it represents only a part of the late Paleozoic to Mesozoic Central European Basin, which was separated during late Cretaceous inversion tectonics. The basement surface below the Subhercynian basin is deepest near the thrusted basement of the Harz (up to 4000 m), where a Late Cretaceous foreland basin developed, and shallows to the north (basement surface in depths of 500-1000 m). Salt-injected folds and some gentle diapirs bring older sediments to the surface. The Beesenlaublingen outcrop belongs to an uplifted area east of the Harz mountains.

Stratigraphy: The pit exposes the top of the Calvörde formation and the first six cycles of the Bernburg formation (fig. 8). These cycles are expressed as units starting with sandstones or oolites with few clay intercalations gradually passing into flaserbedded claystones of varying sand content. The tops of these sandstone-dominated units often show dessication cracks. To the top of one cycle, clay-conent increases, before the next cycle starts with a sudden increase of sand-content.

Sandy claystones of the Calvörde formation form the base of the succession. Their structureless appearance and the occurrence of small anhydrite concretions and strongly dissolved gypsum indicate deposition on a saline mudflat.

Fig. 8: The more than 40 m thick succession of the Beesenlaublingen clay pit exposes lacustrine deposits of the Bernburg formation. Rippled sandstone-claystone units represent the most abundant facies type. Oolites are represented at the base of two cycles.

The basal Bernburg formation starts with the “Hauptrogenstein”, an about 4 m thick unit which is dominated by oolitic limestones following above. The higher parts of the succession consist of rippled or flaser-bedded sandstone-claystone units. They start typically with cross-bedded to laminated sandstones, which may pass vertically into oolitic limestones or a mixed sandy oolithe facies. Magnetostratigraphy (SZURLIES 2003) and biostratigraphy (KOZUR 1999) provide evidence for an early Gandarian age, although endemic species of conchostracans (as the only fossils) and long periods of normal polarity in the early Triassic make a correlation with the international chronostratigraphic scale difficult.

Sedimentology: The about 50 m thick succession and the large area of the pit give the opportunity to observe a variety of sedimentary structures. The most abundant feature is represented by ripple marks. Oscillation ripples are abundant at the top of oolite beds, they occur at the top of sandstone units and form meters thick uniform successions of flaser-bedded sandstone-claystone units. This can be interpreted to represent a very shallow lake facies, where temporary input of sand in a shallow water body was followed by moderate wave action. We assume a delta-like environment above wave base, but the existence of extended sand shoals as proposed by PALERMO et al. (2008), is also likely. Dessication cracks occur preferentially on top of oolite beds and in sandy units at the base of cycles. They give evidence for temporary lake level lowstands. Small gutter casts and hummocks (indicating combined flows of directed currents and waves) occur frequently in the higher parts of the succession. Pocket-like strucktures, up to ten centimetres deep penetrate red laminated claystones in some horizons close to the base of the Bernburg formation. They are filled with loosely packed green ooids. We assume biogenic origin or current action by small wind-induced eddies (scour-and-fill structures, pot casts). Deformation structures are restricted to single units: Some ball and pillow structures point to density inversion during rapid sedimentation; folds and brecciated units could either be caused by slumping or (more probably) by dissolution and precipitation of salt. A striking feature is the complete absence of bioturbation and trace fossils on bedding planes. This allows the preservation of very fine bedding structures like small ripples and lamination.

Interpretation: The large pit is the best exposure of lake deposits of the Lower Buntsandstein in Germany. It shows perfectly the internal architecture of lake deposits and the organisation of oolite bodies. Formation of oolites is restricted to single horizons at the base of the γ-ray cycles. They are interpreted to represent transgressions of the lake, preventing progradation of clastics and thus allowing the establishment of ooid shoals (PALERMO et al. 2008). The absence of any traces of live (with the exception of conchostracans and cyanobakteria) needs explanation. PAUL (2010) assumed strong fluctuations of lake chemistry as the main reason, but also slow recovery of global fauna after the Permian/Triassic extinction event must be taken in consideration in our opinion. Another reason could also be the isolated position of the endorheic lake in the arid climate belt of Pangaea far from other lakes. Together with the lack in flying animals which could act as carrier of larva and fish eggs this would prevent faunal exchange between early Triassic lake systems.

Issues to discuss: An open question is the lack of evaporites in the deposits of the Lower Buntsandstein. All published models propose an endorheic lake in the basin centre. Together with the position of the Central European basin in the arid trade wind belt this would result inevitably in the precipitation of gypsum or salt in some areas of the lake. In fact, no massive evaporites are known. There is only poor evidence for evaporite precipitation like some small marks of lenticular gypsum in some sandstones or strong dolomitisation of ooids which could be explained by the enrichment of magnesium in the course of calcium sulphate precipitation. Two ideas can be discussed: 1) The evaporites could be hidden in the deepest (and in a depth of 10 km inaccessible) parts of the north German basin near Hamburg, or 2) The basin was not closed and had an outflow to the global ocean. The latter is supported by the findings of marine acritarchs in the Lower Buntsandstein of Poland.

Stop 2: Old quarry between Benzingerode and Heimburg

Location: The old quarry is situated between the villages of Heimburg and Benzingerode close to the Harz mountains (fig. 9). It can be reached from the road B6n (exit Heimburg). After 4 km on the road B6 towards Wernigerode, in the centre of the village Benzingerode, close to the church a small road (Ziegeleistraße) leads to the left (eastward). The road must be followed for approximately 1 km to a small junction, where an unpaved forest road leads to the Harz mountains in the south. The outcrop, a trench-like quarry is situated in a conspicuous bush-covered hill, approximately 300 m from the junction.

Coordinates of the stromatolite: 51°49’32’’N, 10°53’11’’E

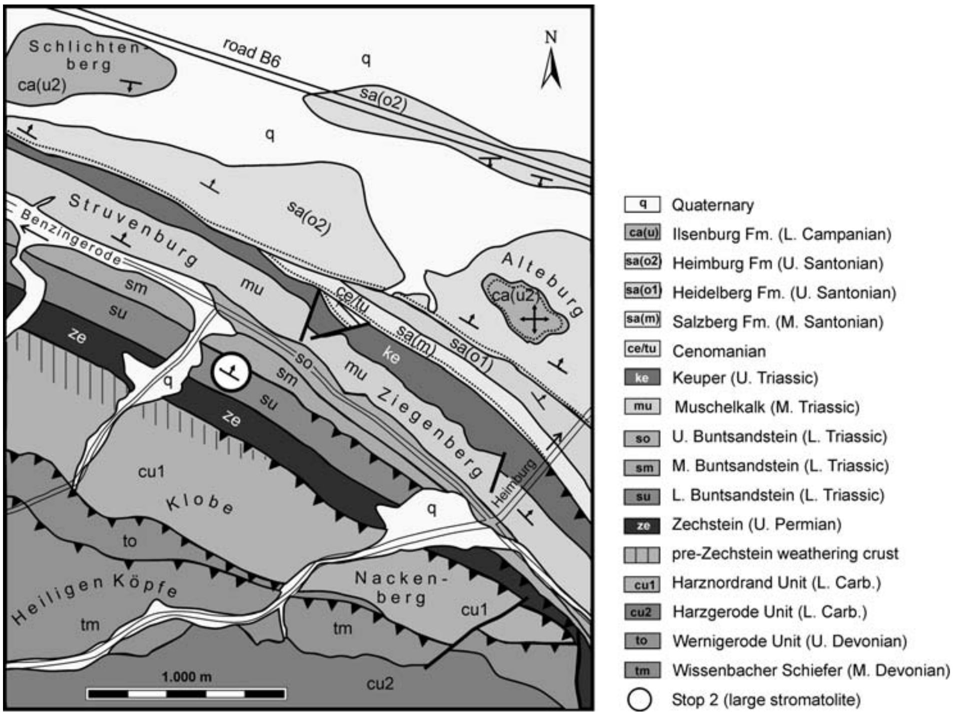


Fig. 9: At the northern margin of the uplifted basement block of the Harz, oolites of the Lower Buntsandstein were quarried. Between the villages of Benzigerode and Heimburg, the biggest known stromatolite of the Lower Buntsandstein is exposed.

Geological situation: The northern margin of the Harz mountains is characterised by a 2-3 km thick upturned succession of Permian to Cretaceous deposits. Nearly the complete basin-fill of the Central European basin is exposed here. The reason is intraplate deformation in the course of Africa-Europe convergence (about 15 km shortening in Central Europe) during late Cretaceous which led to the uplift of basement blocks, folding and thrusting of the basinfill. The Harz mountains represent on of the most prominent basement uplifts. According to geometry of the structure and results of fission track data, the vertical displacement at the northern border is in the order of 10-12 km and occurred in the timespan of only 20 million years.

Stratigraphy: In the narrow trenches, accompanying the northern margins of the Harz over tens of kilometres, oolites (“Rogenstein”) of the Lower Buntsandstein (Bernburg Formation) have been quarried since early medieval ages. The “Rogenstein” was used as a preferred building stone and is present both in Romanic churches and monasteries of the 10th - 12th century (Gernrode, Wöltingerode, Drübeck) and in profane buildings of the villages. They belong to the first cycle of the Bernburg formation (Hauptrogenstein) as the oolites in the Beesenlaublingen quarry visited before. While the oolitic limestones were completely removed from the quarry, the 2.5 m thick, compact stromatolite remained as it was not usable for building purposes.

Fig. 10: The dome-shaped stromatolite of the Benzingerode quarry reaches a size of more than 2.5 m.

Sedimentology: This is the biggest stromatolite ever reported from the Lower Buntsandstein of Germany. Nevertheless it was never investigated in detail and was only mentioned by PAUL & PERYT (2000) in a scientific paper. The stromatolite shows a dome-shaped appearance with the characteristic brain-like, crinkled surface on top. PAUL & PERYT assume that solution due to changing lake chemistry played a major role during formation of these surfaces.

The internal structure is characterized by several growing phases, marked by thin layers of red claystones and even some intercalations of oolites. Although the base of the stromatolite is not exposed, it seams to consist of several smaller stromatolites (LHD-type) which were overgrown and merged to one giant stromatolite cupola. Thin sections prove strong recrystallisation but still show micritic layering of biofilms. The domal structure is composed of several centimetre-thick units, second-order fabric shows branched columns, separated by micritic limestone and silt-sized quartz grains.

Stop 3: Abandoned quarry Heeseberg near Jerxheim

Location: Jerxheim will be reached after 35 km from the medieval town of Wenigerode via the road B 244. Before entering the village, a small road leads to the Heeseberg, (view point, restaurant). A parking site is situated at the restaurant. The better of two outcrops will be reached after 15 min walk along a marked path ("Geologie-Natur-Erlebnispfad"). The abandoned quarry represents the point 6 of the education path. The former quarry-wall is protected (Geotop) and represents the best outcrop of the stromatolitic facies of the Lower Buntsandstein in Germany (RÖBER et al. 2006a, b).

Coordinates: 52°05’01’’N, 10°51’27’’E

Geological situation: North of the Harz mountains, the North-German lowlands extent over more than 250 km to the shores of the North sea and the Baltic sea. Only few smooth hills not higher than hundred metres interrupt the plains. They are formed mostly by gentle domes and diapirs caused by Upper Permian salt or by anticlines and thrusts developed during late Cretaceous deformation of the Central European Basin. The Heeseberg, situated near Jerxheim is one of these structures and belongs to a major thrust system which probably represents a re-activated and inverted normal fault. Thrusting was supported by separation of the sedimentary cover from the underlying basement by thick Permian salt. Together with the Asse fault zone, the Heeseberg structure forms a 50 km long structure that was produced during late Cretaceous basin inversion. During thrusting, Lower Buntsandstein deposits were transported from a depth of about 2000 m to the surface.

Stratigraphy: The Heeseberg section exposes a more than 7 m thick succession of oolites and stromatolites, overlain by red claystones with intercalated calcareous sandstones (fig. 11). It represents the main oolite horizon of the Bernburg Formation, but in contrast to the outcrops visited before, the maximum of oolite thickness is reached one cycle higher and correlates not directly with the “Hauptrogenstein” of the foreland of the Harz mountains.

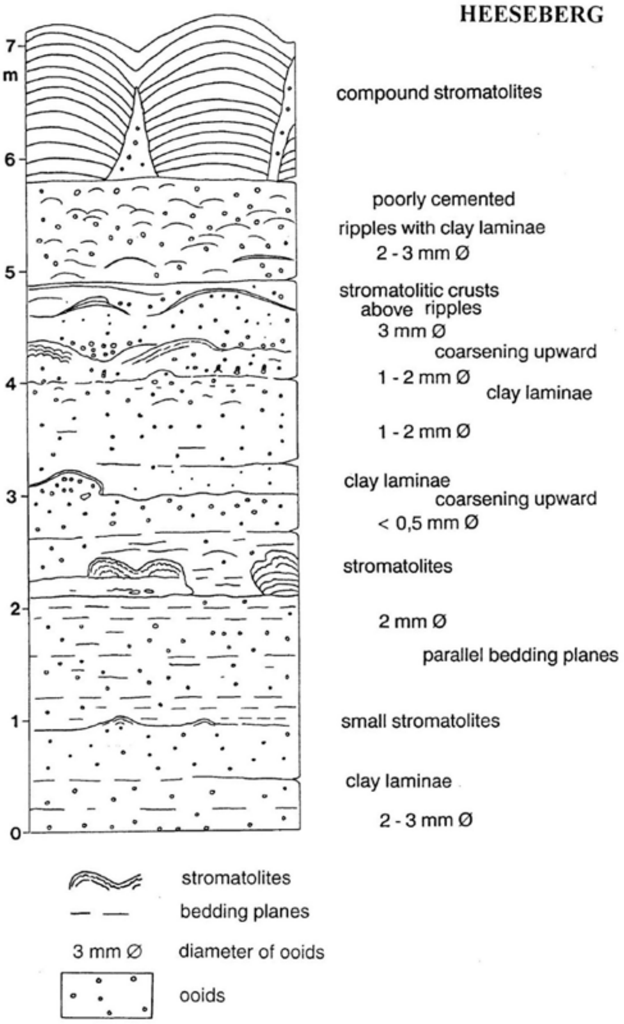


Fig. 11: The Heeseberg quarry is situated on top of the Eichsfeldswell and exposes a section of more than 5 m of pure oolites with some stromatolite layers (PAUL & PERYT 2000).

Sedimentology: A detailed study on the sedimentology of the Lower Buntsandstein was carried out by PAUL & KLARR (1987) at the core of the borehole Remlingen 5. This borehole is situated about 10 km to the west of this outcrop and recovered the whole succession of the Lower Buntsandstein. The Heeseberg succession was investigated by PAUL & PERYT (2000), to exemplify the relationship of ooid-formation and stromatolite growth.

The section consists of horizontally stratified oolites with only few thin clay intercalations. Oolites are often graded. Single units are separated by thin algal mats (stromatolitic crusts) or clay lamina. Most of these surfaces are traceable across the whole outcrop. The most conspicuous feature are a number of stromatolites, arranged in two horizons, but also occurring as small dome-like structures in the oolite beds between these two marker beds. The biggest stromatolites occur in the uppermost horizon, they reach a height of about 1.2 m. The occurrence of oolites and stromatolites ends abruptly with the sudden transition to the overlying clastic succession of red claystones and sandstones.

Interpretation: Oolites and stromatolites are closely related in this section, while the appearance of claystones terminates both stromatolites to growth and ooid formation. This is interpreted to result from poisoning of the carbonate factory by terrigeneous input during lake-level fall (PAUL et al. 2011). Stromatolites are best developed in two single horizons and are associated with the biggest (mostly cerebroid) ooids. PAUL & PERYT (2000) assume an intertidal growth of stromatolites, which is supported by the undisturbed forms of the domal shapes. This assumption would suggest a transport of ooids from the top of the oolite shoal, situated in some distance. Persistent wave action can be excluded on the base of some observation: 1) ooid units are covered by thin stromatolithic crusts; 2) stromatolites grow initially on undisturbed ooid layers, directly from the light-exposed surface of cerebroid ooids; 3) Intraclasts of cemented ooid grainstones form occasionally the substratum for stromatolite growth, thus pointing to early cementation in a quiet environment.

Stop 4: Information Centre Geopark Braunschweiger Land – Ostfalen (Femo) in Königslutter

Location: The Geopark Braunschweiger Land Land-Ostfalen was established to protect and to explain the geological sites of the northern foreland of the Harz mountains. Main attractions are beautiful outcrops of the basin fill of the North German Basin comprising a nearly complete succession from Permian to recent and the numerous findings of late Jurassic to Lower Cretaceous dinosaurs, shown in some museums (Münchehagen, Braunschweig, Hannover). The information centre is situated in the well-preserved medieval town of Königslutter, where some German emperors had temporary their residence during the 12th - 13th century. The grave of emperor Lothar III. († 1135) is located in the Kaiserdom.

Coordinates: 52°15’08’’N, 10°49’02’’E

Stratigraphy: The presented cores belong to the uppermost unit of the Middle Buntsandstein, the Solling formation. PAUL & KLARR (1987) described the core of the borehole Remlingen 5 and interpreted facies to represent lake deposition. PAUL & SIGGELKOW (2004) investigated sedimentology and paleontology of the lake deposits in southern Lower Saxony and published a summary concerning stratigraphy, correlation and interpretation. The main horizon of lake deposits is traditionally named as “Graue Tonsteinschichten” (Grey claystone beds). The thickness of these beds fluctuates between 5 and 10 m. They follow above calcareous grey sandstones of only 1-2 m thickness. At the top, the

“Graue Tonsteinschichten” are overlain by red claystones with intercalations of sandy siltstones of about 12 m thickness with abundant mud clasts and dessication cracks, interpreted to represent a mud flat (PAUL & KLARR 1987). The Solling formation ends with a unit of thick cross-bedded sandstone (about 17 m), representing a braid plain prograding into the playa.

Sedimentology: The basal sandstones below the Grey claystone beds are structure-less apart from some clay drapes. To the top, mud clasts and water escape structures occur. Laminated grey claystones are the main facies type of the “Graue Tonsteinschichten”. These claystones have a varying carbonate content of 15-30% (calcite and iron-rich dolomite) and contain framboidal pyrite and galenite. High amounts of uranium (100-700 ppm) and other heavy metals are a typical feature of this unit. Total organic carbon was determined to be in the order of only 0.15-0.69%. The whole section contains thin streaks of silt and fine sand, often graded. Gamma-ray logs indicate a clayey upward succession. Some of the thicker sand and silt units are cross-bedded. Bioturbation is absent. No fossils benthic fossils occur. The traces of live are limited to spores and pollen and fine plant debris. Additionally, some marine acritarchs and prasinophytes occur.

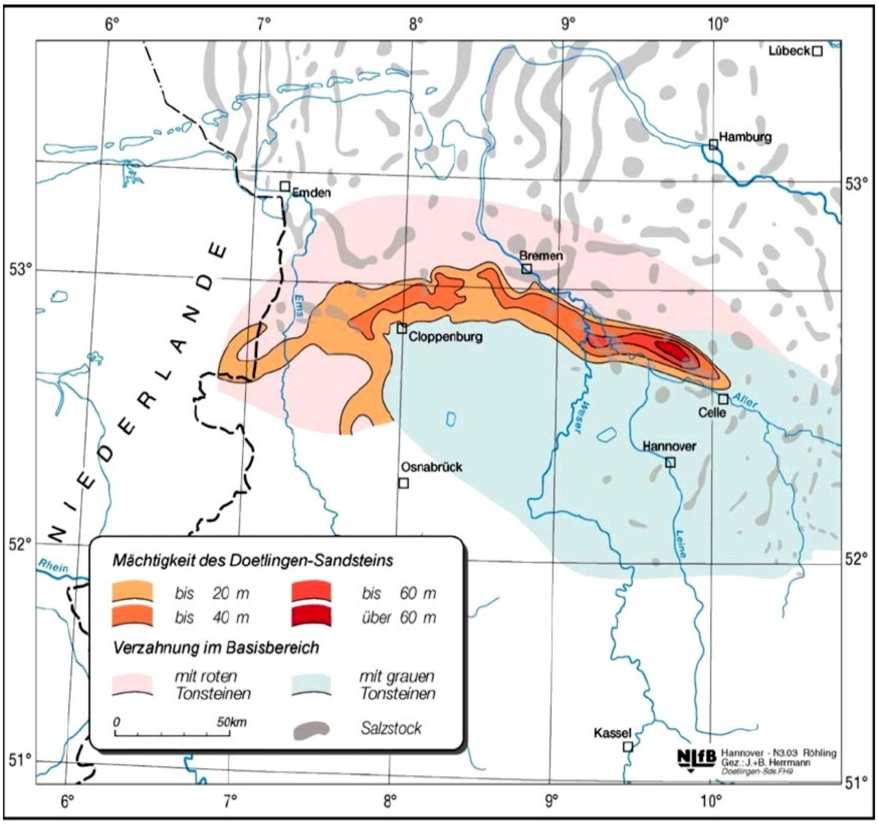


Fig. 12: Lake deposits of the Middle Buntsandstein (Solling Formation) are widely distributed in the subground of Lower Saxony. A sandstone belt divides grey claystones of a meromictic lake from red clay- and sandstones of a more oxygenated facies in the north (RÖHLING & SCHULZ 2000).

Interpretation: The grey claystones with varying sand content form a conspicuous horizon within the stratigraphy of northwest Germany and extent over tens of kilometres. PAUL & SIGGELKOW (2004) interpreted a shallow, meromictic lake with a stable stratification caused by increased salinity of bottom waters. The limited thickness of the grey claystone unit indicates only a short existence of the lake. The authors estimate duration of lake sedimentation to be in the order of 10,000 to 50,000 years with a sedimentation rate of 0.1 to 1 mm/y. The extension of the lake was probably twice the size of the recent lake Tschad. Schulz & Röhling (2000) investigated the regional distribution of the grey claystones at the base of the Solling Formation. They determined the northern boundary of these lake deposits in the middle of northern Lower Saxony where they interfinger with a narrow sandstone belt, the Dötlingen sandstone (fig. 12). Röhling (1986, 1988) and Schulz & Röhling (2000) interpreted it as a sand shoal. North of it, red oxygenated clays prevail, interpreted to represent the oxygenated, high energy lake facies.

Stop 5: Old quarries west of Großwangen

Location: Large abandoned quarries extent along the Unstrut river west of the village Großwangen. Here, dolomitic sandstones and red claystones of the Lower Buntsandstein are exposed which are overlain by sandstones of the Middle Buntsandstein. Wangen is situated near the town of Nebra and is famous for a spectacular archaeological site; the 4000 years old Sky Disc of Nebra was found here. Großwangen will be reached from the road B 250 from Querfurt and a local road leading from Nebra to the small village of Wangen. The sandstone quarries are situated immediately west of the village and can be reached by a path following the quarry walls.

Coordinates: 51°16’02”N, 11°32’14”E

Geological situation: South of the Harz mountains which represent an uplifted basement block of Palaeozoic folded and metamorphosed sediments, a large syncline is developed in the overlying succession of about 2000 m thick Upper Permian to Triassic deposits (Thuringian syncline). Großwangen is situated in the northern part of this structure. The Buntsandstein dips with a few degrees towards the northeast reflecting two substructures of the northern Thuringian syncline, the Bibra anticline and the Querfurt syncline. The Lower Buntsandstein of this area shows the transition from the lake facies (indicated by ooid beds) to the southern sandplains (fig. 13).

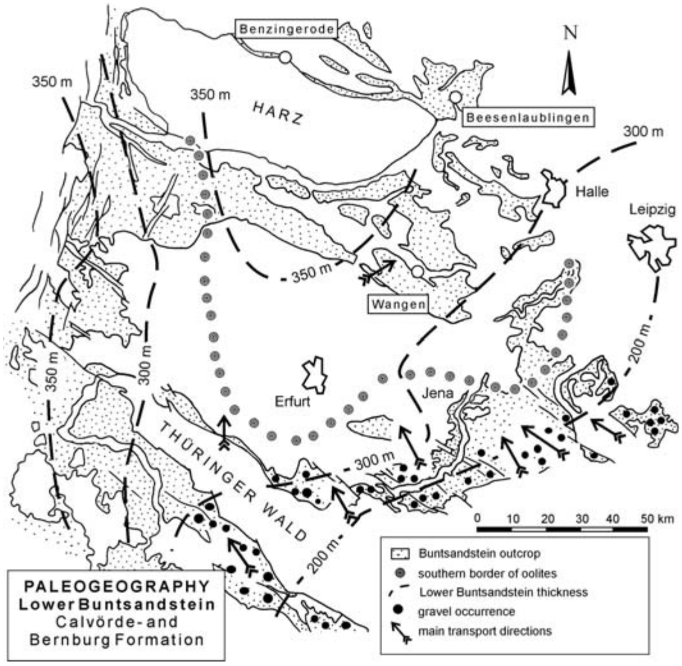
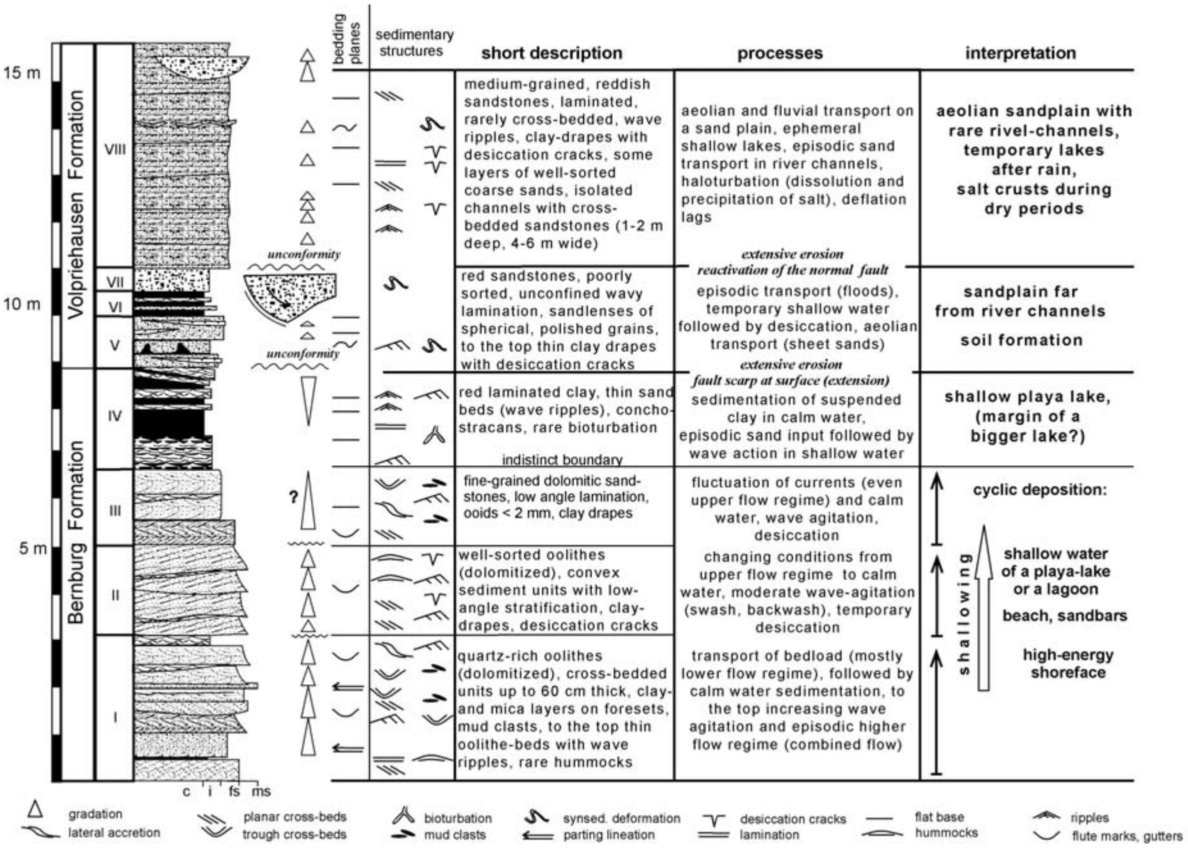


Fig. 13: The lake margin of the Lower Buntsandstein forms a bight towards the south, which can be mapped in the Thuringian syncline between the Harz mountains and the Thüringer Wald, reflected both from the southern boundary of oolite beds as by thickness distribution. (modified from VOIGT & GAUPP 2000).

Stratigraphy: The about 15 m tick whitish to light-grey sandstones at the quarry base belong to the uppermost part of the Lower Buntsandstein, the Bernburg formation (fig. 14). Correlations on the base of the gamma logs according to RADZINSKI (1995) point to cycle 8 of the Bernburg formation. The sandstones are overlain by 2.5 m thick red claystones with some rippled sandstone beds which still belong to the Bernburg formation.

The following medium- to coarse-grained, reddish sandstones (30 m) represent the base of the Volpriehausen formation, the first unit of the Middle Buntsandstein. The upper cycles of the Bernburg Formation were probably eroded.

A conspicuous feature of the succession is the existence of synsedimentary normal faults at the base of the Middle Buntsandstein. In the visited outcrop, they form a small (2 m deep) graben structure. This is the only place in Germany there synsedimentary extensional tectonics are obvious in outcrop although a short-term change of intraplate stresses is also indicated by significant changes in thickness deduced from seismic sections and log correlations (BOIGK 1959, WOLBURG 1962, HERMANN 1961). The resulting gentle unconformity, traceable at the Eichsfeld-Altmark and the Hunte swell, is called the Volpriehausen Unconformity ("V-Diskordanz").



short description	processes	interpretation
medium-grained, reddish sandstones, laminated, rarely cross-bedded, wave ripples, clay-drapes with desiccation cracks, some layers of well-sorted coarse sands, isolated channels with cross-bedded sandstones (1-2 m deep, 4-6 m wide)	aeolian and fluvial transport on a sand plain, ephemeral shallow lakes, episodic sand transport in river channels, haloturbation (dissolution and precipitation of salt), deflation lags	aeolian sandplain with rare rivel-channels, temporary lakes after rain, salt crusts during dry periods
red sandstones, poorly sorted, unconfined wavy lamination, sandlenses of spherical, polished grains, to the top thin clay drapes with desiccation cracks	episodic transport (floods), temporary shallow water followed by desiccation, aeolian transport (sheet sands)	sandplain far from river channels soil formation
red laminated clay, thin sand beds (wave ripples), conchostracans, rare bioturbation	sedimentation of suspended clay in calm water, episodic sand input followed by wave action in shallow water	shallow playa lake, (margin of a bigger lake?)
fine-grained dolomitic sandstones, low angle lamination, ooids < 2 mm, clay drapes	fluctuation of currents (even upper flow regime) and calm water, wave agitation, desiccation	cyclic deposition: shallow water of a playa-lake or a lagoon
well-sorted oolithes (dolomitized), convex sediment units with low-angle stratification, clay-drapes, desiccation cracks	changing conditions from upper flow regime to calm water, moderate wave-agitation (swash, backwash), temporary desiccation	beach, sandbars
quartz-rich oolithes (dolomitized), cross-bedded units up to 60 cm thick, clay- and mica layers on foresets, mud clasts, to the top thin oolithe-beds with wave ripples, rare hummocks	transport of bedload (mostly lower flow regime), followed by calm water sedimentation, to the top increasing wave agitation and episodic higher flow regime (combined flow)	high-energy shoreface

Fig. 14: The Wangen section exposes the transition from Lower Buntsandstein (Bernburg formation) to the Vopriehausen Formation of the Middle Buntsandstein (modified from VOIGT & GAUPP 2000). As the Dolomitic Sandstone represents the 8th cycle of the Bernburg Formation according to correlations of RADZINSKI (1995), major erosion is assumed. Synsedimentary faults are observed near the boundary of formations.

Sedimentology: The dolomitic sandstones of the Bernburg formation form a conspicuous horizon traceable over a vast area from the northern foreland of the Harz mountains to the northern part of the

Thuringian syncline between Halle and the Kyffhäuser mountains (50 km across). The unit is composed of light-grey, well-sorted sandstones with few intercalations of green claystones (fig. 15). Thin-sections show that sandstones contain quartz, up to 20% feldspar and a varying quantity of ooids. In some distinct layers ooids even prevail. Grains are cemented by dolomite; the original calcite of ooids is also completely replaced by blocky dolomite cement. Ghost structures of the primary coatings are marked by brownish (organic?) inclusions. Sedimentary structures are dominated by cross-bedding, low angle bedding and lamination. Oscillation ripples occur frequently especially on top of single units. Transport directions vary significantly and indicate strongly fluctuating current directions. Most of the sedimentary units are grouped to convex bodies with a flat base, followed by draping clay-sandstone units of some cm thickness. Erosion of current ripples occurred frequently and gave way to the formation of reactivation surfaces.

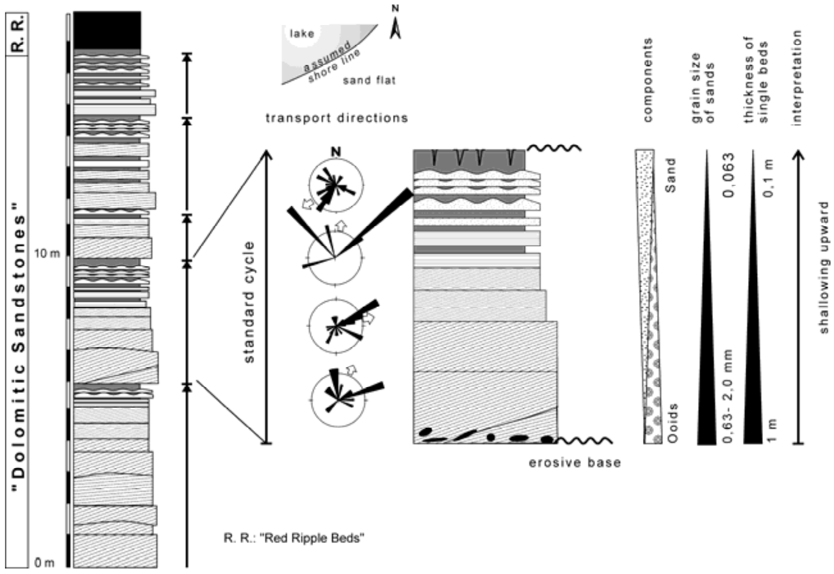


Fig. 15: Units of cross-bedded and low-angle stratified sands, followed by sand- and claystones with wave-ripples are a characteristic feature of the light-grey dolomitic sandstones of the Wangen section. To the top, thickness of units decreases. Similar sandstones are distributed along the southeastern margin of the Lower Buntsandstein lake, but occurrence in different cycles of the Bernburg Formation point to significant shifts of the coast line (modified from Voigt & Gaupp 2000).

The dolomitic sandstones are covered by a red claystone unit with intercalated sandsheets. Claystones are laminated and contain conchostracans. Sandstone beds reach a few centimetres thickness and show flat bases, but rippled surfaces (symmetric wave-ripples). They are followed by the basal sandstone of the Volpriehausen formation: a 30 m thick unit of red, green and white sandstones, poorly sorted, with thin clay drapes and lenses of coarse, well-rounded coarse sands. At the base they contain some small quartz granules (up to 5 mm) and some units of green to wine-red claystones with a lot of desiccation cracks in every horizon. Most of the sandstones are horizontally bedded, but in some horizons, saucer-shaped structures of more than 1 m size and other deformation structures can be observed. A fluvial channel is visible in the outcrop, about 10 above the base of the Volpriehausen formation.

Interpretation: The basal unit represents the uppermost part of the Bernburg formation and is interpreted to be deposited at the margin of the Buntsandstein lake (Voigt & Gaupp 2000). Mixing of ooids and sand indicates an allochthonous facies belt in the transition from carbonatic lake deposits (deposited from sands) to a terrigeneous facies belt (delta or shore). According to the observed sedimentary structures, this facies type is interpreted to represent a lake margin facies characterized by breaking waves producing low angle beach lamination and strong wind-induced along shore currents (VOIGT & GAUPP 2000). The high thickness of these deposits in a NE-SW-striking belt indicates a long term fixed position of the coast line during the deposition of the higher Bernburg formation. Similar deposits occur in the Lower Bernburg Formation of eastern Thuringia (FENSTERER & VOIGT 2010), indicating basin-ward shoreline migration of about 50 km. In the Großwangen outcrop, the transition to red claystone and sandstone deposition marks the final destruction of the carbonate factory of the Lower Buntsandstein lake system in this part of the basin.

The red-coloured claystone-sandstone unit is characteristic for a small lake or a lagoon dominated by temporary clastic river input, which was reworked by wave action. Progradation of a river mouth is indicated by the increasing thickness of sandstone beds and decreasing amount of clay in the succession.

The following sandstones of the Volpriehausen formation are characteristic of sandplains dominated by aeolian processes and temporary lakes. They are dissected by only few fluvial channels. Tepee structures and destratified mudstones indicate a salty mud flat influenced by frequent precipitation and dissolution of salt both in the subsurface and on the surface of the sandflat. The existence of salt crusts is indicated by irregular distribution of sand patches in some units. Lakes existed temporarily, but millimetre-thin layers of green clay, dissected by desiccation cracks indicate limited size and rapid drying.

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