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Sedimentology of a Permian playa lake: the Boda Claystone Formation, Hungary

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Abstract

The Upper Permian Boda Claystone Formation (BCF) in SW Hungary has been previously been identified as a saline lake deposit. A country-wide screening found this 800–1000 m thick succession the most suitable for the disposal of high-level radioactive waste in Hungary, and research into this formation has consequently been intensified since. The investigations included a detailed study of the sedimentological characteristics. Data obtained by mapping of the 25 km^2 outcrop area of the formation and from more than 40 boreholes were processed. The sedimentary structures were investigated on outcrop to microscopic scales, and cycles in the succession were interpreted.

The main lithofacies, sedimentary structures and ichnofossils are presented. They indicate that the major part of the succession was deposited in a playa mudflat and is not of lacustrine origin in a strict sense. The lake sediments are represented by laminated and ripple-marked/flaser-type cross-laminated claystones and siltstones and by massive dolomites; trace fossils include crawling traces and burrows. Partial or complete drying out of the lake commonly occurred after the formation of carbonate mud by evaporation. Periodic fluvial influx is recorded by cross-bedded sandstones and unsorted gravelly sandstones of up to pebble-sized angular grains. Fenestral and stromatolitic structures reflect the repeated appearance of playa mudflat conditions. The silty claystones, which compose the major part of the succession, lost their primary structures due to pedogenic processes and indicate prolonged subaerial intervals with soil formation and only ephemeral inundations. The presence of pedogenic carbonate concretions supports the interpretation of an arid climate and a relatively shallow groundwater table. Drying-out events shown by desiccation cracks and authigenic breccias can be traced all over the succession.

The various facies form small-scale sedimentary cycles showing a shallowing-upward trend and the growing influence of aridity and subaerial exposure.

Keywords: Late Permian, Boda Claystone Formation, Hungary, playa

Introduction

The Upper Permian Boda Claystone Formation (BCF) occurs in the Mecsek Mountains in SW Hungary (Figs. 1, 2). A country-wide screening found this 800–1000 m thick succession the most promising for the disposal of high-level radioactive waste in Hungary;

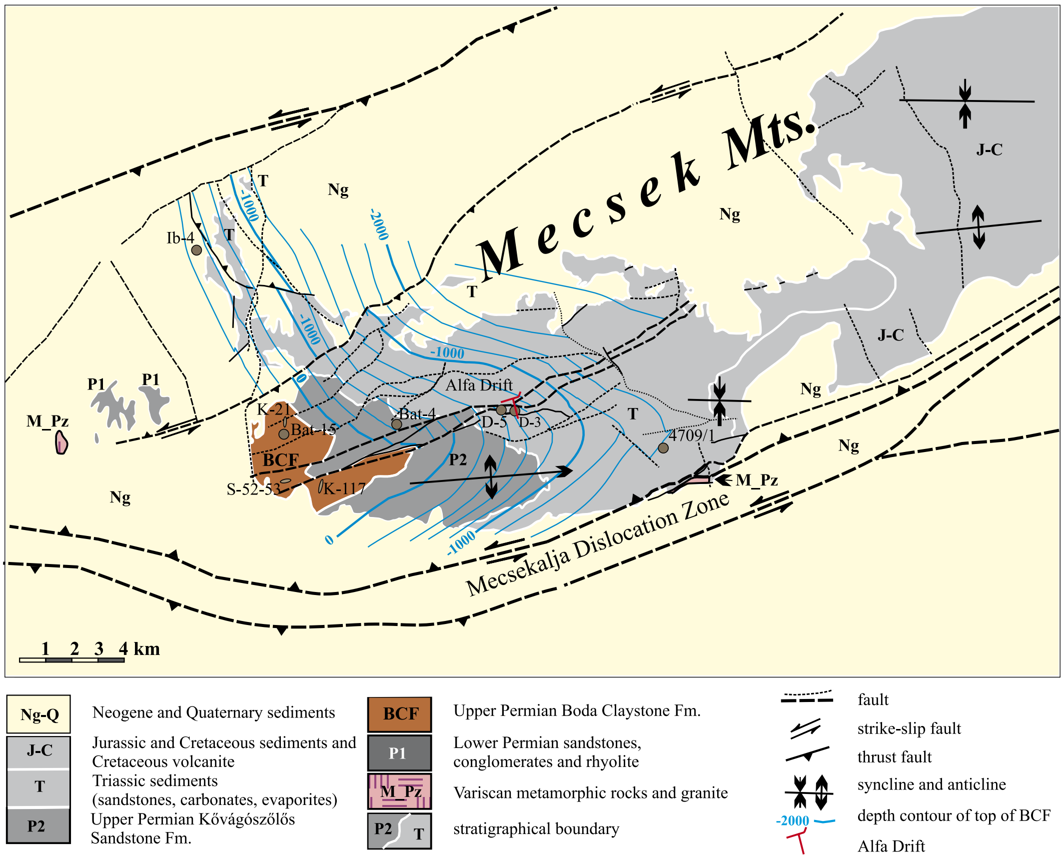

Fig. 1. Geological map with depth contours of the top of the Boda Claystone Formation.

research into this formation has consequently been intensified since (Kovács et al., 2000; Konrád & Hámos, 2006). One of the primary objectives of the research project was to assess the lateral and vertical homogeneity of the formation; investigations included a detailed study of the sedimentological characteristics. Data obtained by mapping the 25 km^2 outcrop area of the formation and from more than 40 boreholes were processed for the purpose. Sedimentary structures were investigated on outcrop to microscopic scales, and a cycle stratigraphical interpretation of the succession was carried out.

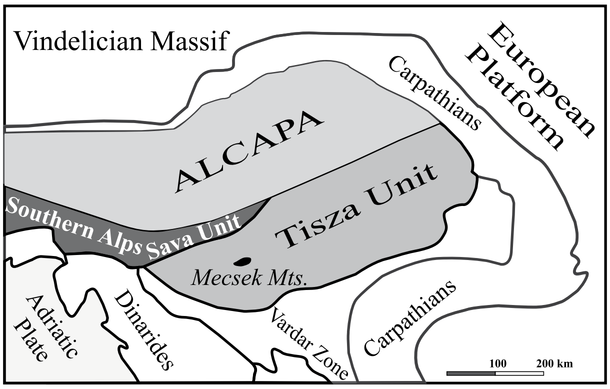

Fig. 2. Overview of plate tectonic units in the Pannonian Basin (after Haas & Péró, 2004).

Since no sedimentological description of the formation has been published yet, the present contribution is the first of its kind. Objectives of the study are therefore to provide an overview of the formation, to supplement existing data with new observations on sedimentology at all scales, and to interpret these data; these have resulted in a partial modification of the previous – and until now generally accepted – ideas about the sedimentary environment.

Geological setting

The study area is part of the Tisza Unit, the Mesozoic microplate now comprising the basement of the south-eastern half of the Pannonian Basin. In the Permian, this unit was located north of the equator and belonged to the southern margin of the stable European plate

(Csontos & Vörös, 2004), where a thick continental clastic succession accumulated. Continental (molasse) sedimentation started here after the Variscan orogeny, in the Late Carboniferous. This sedimentary megacycle lasted until the Middle Cretaceous and comprised several second-order cycles. The transitional and playa sediments of the BCF are located within the Permian fluvial succession. In contrast to the other Permian sediments of the region, the Boda Claystone Formation, with a known distribution area of only approximately 150 km^2, represents a relatively small, continuously subsiding basin. This was one of the continental strike-slip and rift-related basins in the northern part of the internal Variscan orogenic domain (Vozárová et al., 2009).

While phyllopods from the lower unit of the formation point to a Cisuralian age (Fülöp, 1994), the sporomorphs indicate the Guadalupian-Lopingian (Barabás-Stuhl, 1981). Vozárová et al. (2009) consider the Guadalupian-Lopingian age better constrained. In their stratigraphical chart, they attribute the BCF to the Guadalupian; in the present contribution, we follow this dating.

The outcrops of the BCF are connected to the perianticlinal structure of the W Mecsek Mountains. This anticline dips downward to the North and East, whereas it is eroded on the western side and tectonically displaced on the southern side. The anticlinal structure is affected by the Cretaceous orogeny and is bounded in the South by a left-lateral strike-slip fault zone. The Mecsek Mts. constitute a positive flower structure in a shear zone.

Within the generally coarse-grained fluvial Permian succession, the BCF is characterised by a smaller grain size (clay to silt). It shows a gradual transition from the underlying Cserdi Fm.; its lower boundary has been defined to be located where conglomerate intercalations disappear and fine-grained sandstones and siltstones start to dominate. The upper boundary is usually sharp but can be transitional as well; it is marked by the appearance of conglomerates at the bottom of the Kővágószőlős Sandstone Fm. The BCF interfingers at the basin margins with the underlying and overlying formations (Cserdi and Kővágószőlős Formations) as a heteropic basin facies (Barabás & Barabásné Stuhl, 1998).

The Boda Claystone Formation comprises three main units (Konrád, 1999) (Figs. 1, 3-A):

1) a lower transitional sandstone 100–150 m thick, characterised by fine-grained sandstone beds;
2) a 350–450 m thick middle albitic claystone/siltstone with sandstone beds and characterised by cm to dm thick micaceous siltstone and fine-grained sandstone intercalations;
3) an upper claystone, albitic clayey siltstone and silty claystone with a thickness of 400–500 m, with dolomite and siltstone beds showing desiccation cracks and, in the upper part of the succession, septarian dolomite concretions.

Units 2 and 3 have been interpreted as deposits of a saline lake under semi-arid climate (Hámos et al., 1996).

Sedimentological characteristics

Rock types distinguished by mineralogical composition and grain size

The dominant minerals of the formation are quartz, clay minerals, albite, carbonates and hematite. The mean hematite/FeO ratio is 7, resulting in brown to red colours, except for occasional green claystones and siltstones and whitish dolomites. The mineralogical composition has been described by Máthé (1999), Árkai et al. (2000) and Varga et al. (2005). Based on their descriptions and on our new data, the following rock types can be distinguished considering the ratio of lithoclasts and the main mineral components: (1) polymict conglomerate, (2) arkosic sandstone, (3) siltstone, (4) claystone-albitolite, (5) green claystone and siltstone, and (6) dolomite.

Polymict conglomerate

Fine-grained conglomerates occur in the lower, so-called transitional unit of the formation (Fig. 4). In the upper 800 m of the formation, conglomerates have only been recorded

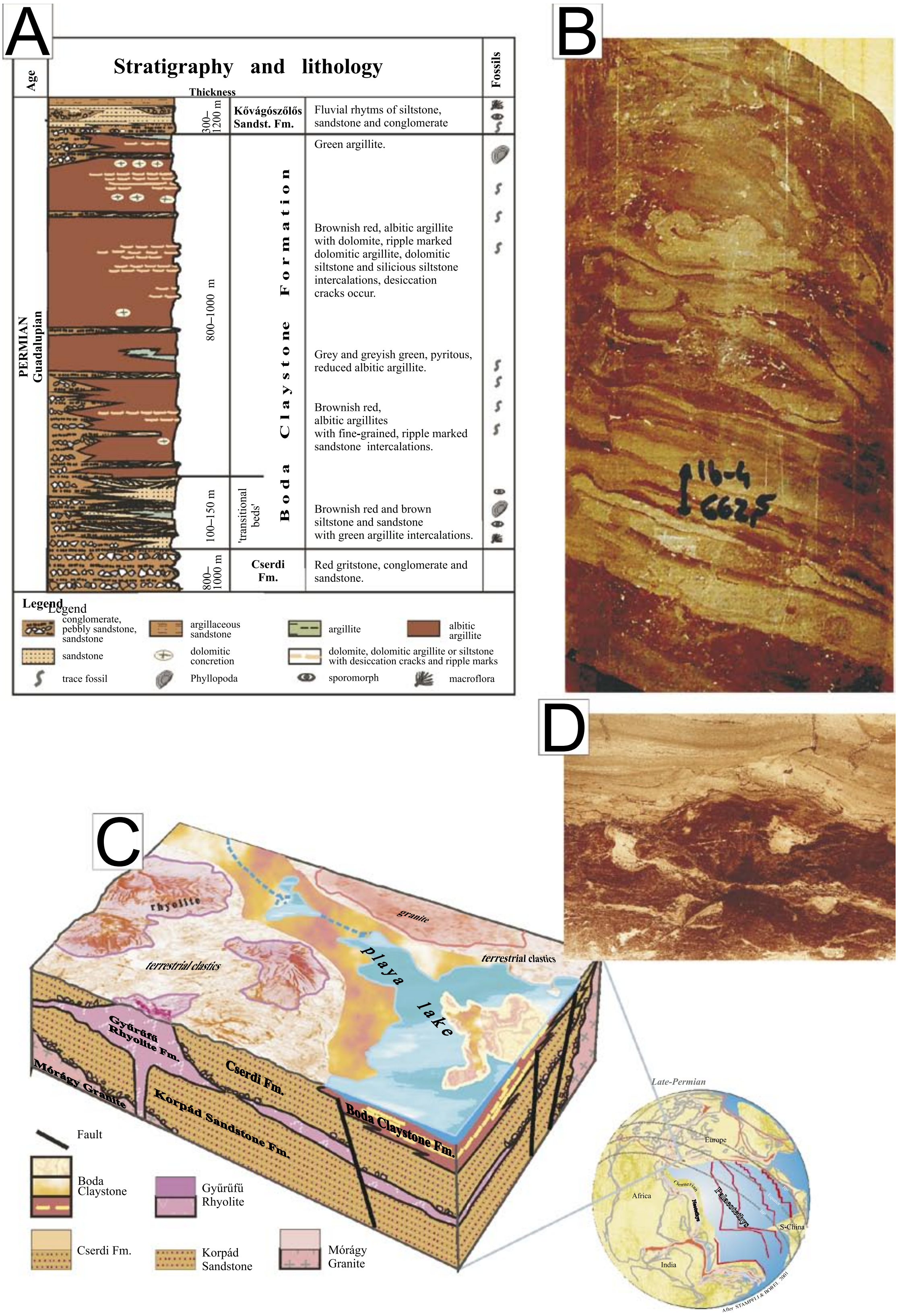

Fig 3. Lithology and palaeogeography and some sedimentary structures of the Boda Claystone Formation. **A** – Idealised lithological column; **B** – Contorted bedding in the borehole Ib-4, 662.5 m. Diameter of drilling core is 6 cm; **C** – Palaeogeographical and palaeomorphological reconstruction; **D** – Disturbed structure from the borehole Bat-4, 1109.2 m. Image height 2 cm.

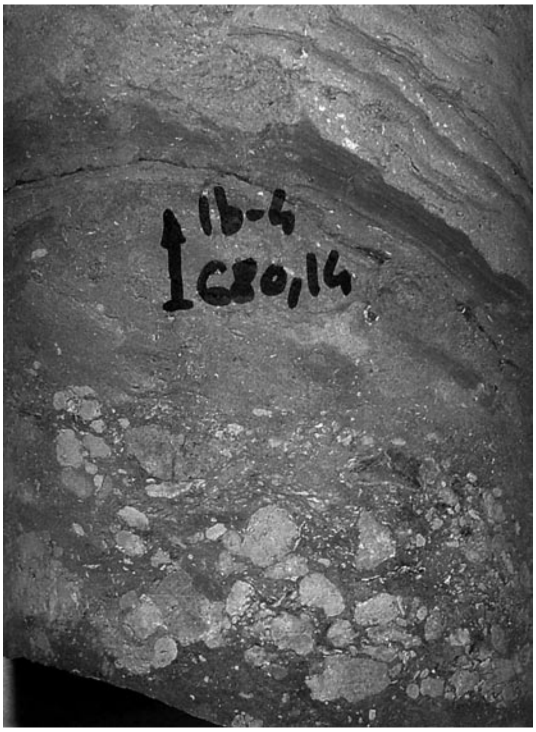

Fig. 4. Conglomerate-siltstone-claystone cycle from the lower, transitional unit of the formation. Drilling core from borehole Ib-4, 680.14 m, image width 5 cm.

so far from borehole 4709/1 on the eastern margin of the known extent of the BCF, where they represent a basin-margin facies.

The composition of the conglomerate is identical to that of conglomerates in the over- and underlying formations: they were derived primarily from granite, rhyolite and metamorphic rocks, but reworked intraformational siltstone pebbles are also common.

Arkosic sandstone

Sandstone layers are common in the lower, transitional part of the formation; upwards they become less frequent. They contain muscovite of various sizes and amounts.

Siltstone

The siltstones are characterised by varying amounts of clay minerals, albite and carbonates. Their typical mineral components are quartz, illite, muscovite and authigenic albite as a cement. They occur as thin intercalations.

Claystone-albitolite

This rock type, characterised by varying albite, quartz and dolomite contents, dominates the formation. It is red-coloured due to its 6–10% hematite. The dominant clay mineral is illite-muscovite. Chlorite is less abundant; its amount is considerable only in the reduced, green beds. Albite appears in nodules of various shapes and of diameters of max. 3 mm, typically together with carbonates, or as an impregnation/cement. Composition, structure and texture prove the authigenic formation of the albite: a pure Na end member, with ordered, low-temperature structure (Árkai et al., 2000). Euhedral analcime crystals from borehole Ib-4 (Németh et al., 2005) prove the previously supposed analcime-to-albite transformation (Majoros, 1999). The amount of albite can exceed 50%.

Green claystone and siltstone

Green and greenish-grey siltstones and claystones occur infrequently. The colour originates most commonly from postdepositional reduction of the breccia clast margins (Fig. 5-G). Much less frequently (in only very few cases) it affects entire layers. These rocks have higher chlorite and kaolinite concentrations, the latter mineral indicating more intense chemical weathering. Pyrite occurs in these layers as well.

Dolomite

Dolomites have varying clay-mineral, albite and quartz contents. They occur as intercalations and are characterised by desiccation cracks. The quartz is present as silt grains. The clay mineral is illite-muscovite, occasionally accompanied by hematite.

Rock types differentiated by mineral composition are plotted in Figure 6. Illite shows a negative (-0.8) correlation with albite and a positive one (0.7) with hematite. This relationship is reflected in the more reddish colour of the claystones.

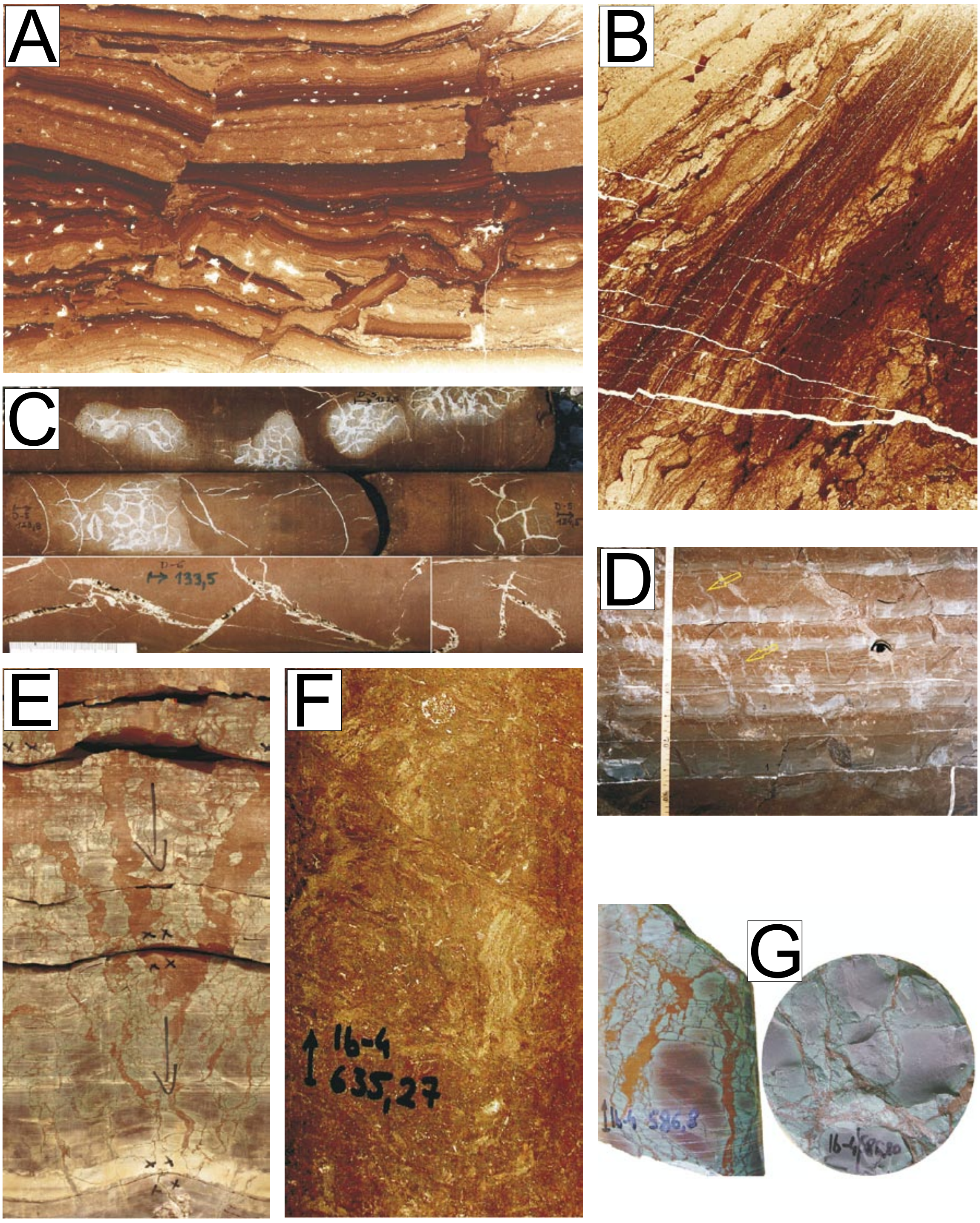

Fig 5. Sedimentary structures in the Boda Claystone Formation.

A – Thin section of desiccated dolomite beds from the borehole Delta-3, 238.5 m. The carbonate-filled cavities show a fenestral structure, the fine lamination has a stromatolitic character. Image width is 3 cm; **B** – Enterolithic and nodular structure from the borehole Bat-15, 21 m. Thin section; image width 18 mm; **C** – Septarian carbonate concretions from the Delta-5 borehole (top) and synaeretic(?) cracks in claystone (bottom) from the borehole Delta-6. Diameter of the drilling cores is 6 cm; **D** – Tepee structures in dolomite beds in the exploration drift 'Alfa' excavated from the former uranium mine. Arrows mark a desiccation crack penetrating 1.5 m of sediments, including previous, already desiccated dolomite layers; **E** – Breccia covering a dolomite bed in the borehole Ib-4, 587 m. Scanned surface of a drilling core; perimeter of core (and image width) is 38 cm; **F** – Pedogenic structure from the borehole Ib-4, 635.27 m. Arrow on drilling core is 1 cm; **G** – Breccia structure in the borehole Ib-4, 586.8 m. Clast margins are chloritised, the matrix is red clay. Diameter of the drilling core is 6 cm.

Texture of the sediments

Conglomerate

Grain-supported conglomerate intercalations occur in borehole 4709/1. They are poorly sorted; the pebbles are angular to subangular, and their maximum size is 8 cm. The matrix is composed of subangular coarse-grained sand.

Sandstone

The occurrence of sandstone beds is characteristic of the lower, transitional part of the formation. Upwards they appear as intercalations and become finer-grained and less frequent. Sandstones are also common in the succession of the basin margin in borehole 4709/1.

The sandstones of the transitional beds are well-sorted and typically fine- to medium-grained; muscovite flakes are commonly oriented parallel to the bedding. In the marginal facies of the basin, the sandstones occur together with dolomitic claystones and conglomerates, and they are poorly sorted there. The grains are usually subangular to subrounded.

Siltstone

The siltstones are well-sorted and may contain fine sand grains. Small muscovite grains are common and only exceptionally show a preferred orientation.

Clayey siltstone to silty claystone

These sediments represent a transition between claystone and siltstone and make up the bulk of the formation.

Claystone

Pure claystones occur only rarely. They are very well sorted; the occasional muscovite grains show no preferred orientation.

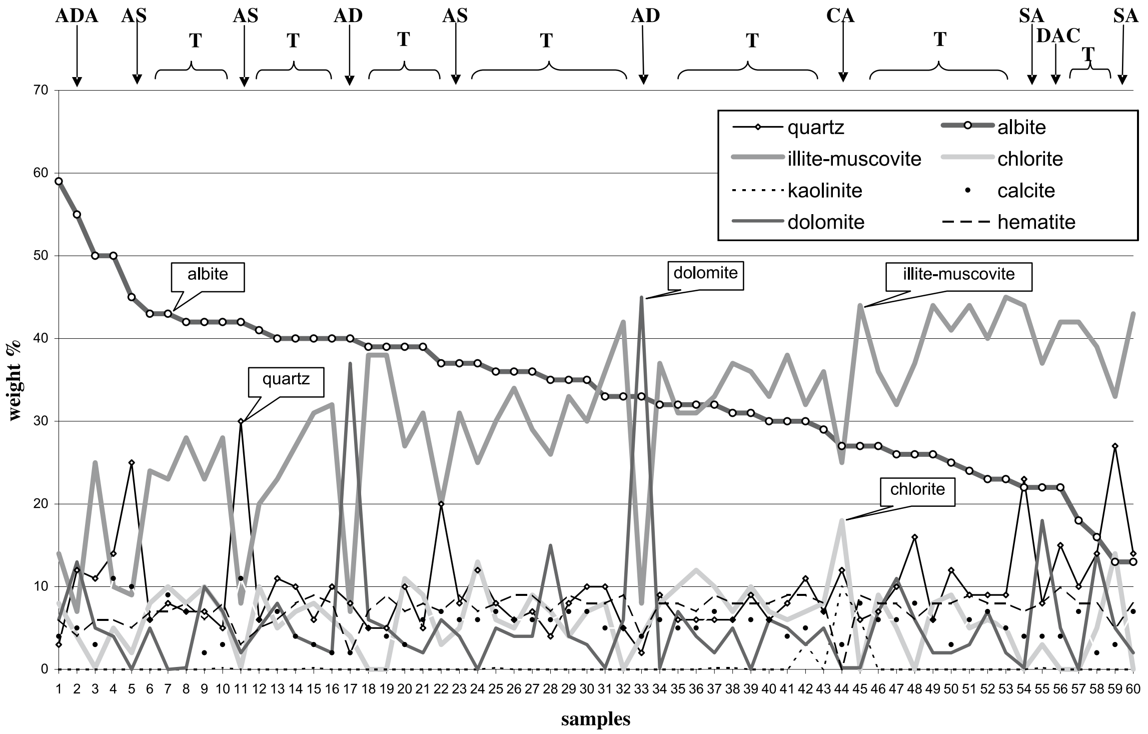

Fig. 6. Typical mineralogical composition of the fine-grained rock types of the Boda Claystone Formation. The weight % composition of the 60 samples was calculated by Máthé (1999) based on XRD and DTG measurements and silicate chemical principal component analysis. Samples are ordered according to their albite content. It is apparent that the amount of clay minerals increases with decreasing albite content. In sandy intercalations, the clay minerals are substituted by quartz, in dolomite beds by dolomite. In the typical rock type (T), albite and illite-muscovite make up 50-75%, other components are below 16% each; other characteristic rock types are argillaceous dolomitic albitolite (ADA), albitic siltstone (AS), albitic dolomite (AD), albitic claystone (AC), albitic sandy claystone (SA), chloritic claystone (CA) and dolomitic albitic claystone (DAC).

Dolomicrite, clayey dolomicrite and silty dolomicrite

The dolomite layers are micritic. They may contain clay minerals and silt grains scattered or in the form of intercalated laminae.

Sedimentary structures

Synsedimentary structures

The following types of synsedimentary structures occur in the BCF:

1) Horizontal bedding (planar lamination). This bedding type occurs in both sandstones and siltstones. Dolomites with clay laminae and rarely the claystones also show horizontal bedding (Fig. 7), often overprinted by secondary sedimentary structures (Figs. 6A, D). In unbedded claystones and clayey siltstones, elongated 0.1–2 mm long cavities filled with carbonate or albite indicate the bedding direction (Fig. 8).
2) Cross-lamination. Ripple marks (Fig. 9) and symmetrical or slightly asymmetrical cross-lamination are common in the siltstones and sandstones. Small current ripples with trough cross-bedding are typical, with tangential or sigmoidal cross-laminae (Figs. 10–11).
3) Stromatolite structures. Fine lamination in the sediment occasionally resembles a stromatolitic structure (Fig. 5A). These occurrences are usually connected to dolomite intercalations. Less frequently, a similar fine lamination can be observed in claystones as well.
4) Fenestral structures. Fenestral structures are caused by carbonate-filled bird's eye-type hollows. The maximum size of these cavities is a few mm, their typical size is around 1 mm. They may represent primary fluid or gas inclusions, and were flattened by lithostatic pressure (Figs. 5A, 8).

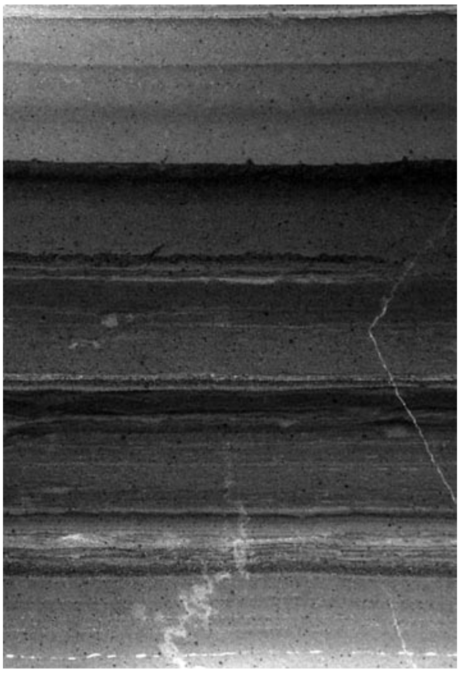

Fig. 7. Horizontal lamination in claystone from the middle part of the formation (outcrop K-21); image width 1 cm.

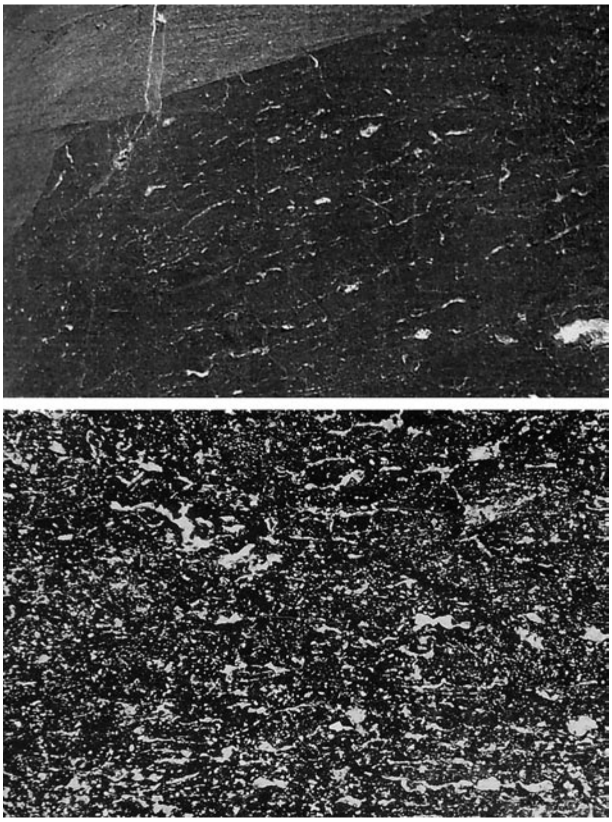

Fig. 8. Irregular cavities (fenestral structure) in claystone filled with carbonate and in most cases also with albite. They are flattened parallel to the bedding. Top: surface of drilling core (borehole Ib-4, 576.7 m); bottom: thin section (borehole Bat-4, 700.3 m, one nicol). Width of both photos is 20 mm.

Fig. 9. Ripple marks on the bedding plane of a siltstone intercalation in claystone.

Postsedimentary structures

The observed postsedimentary structure types are the following:

1) Raindrop imprints. Raindrop imprints are occasionally present on bedding planes dissected by desiccation polygons.
2) Enterolithic and nodular structures. Dolomitic intercalations occasionally show enterolithic and/or nodular structures (Fig. 5B). These must have been formed by the dolomitisation of primary anhydrite nodules.
3) Shrinkage cracks. Carbonate concretions are common in the upper part of the formation and they often show a septarian structure (Fig. 5C) caused by synaeresis. Though rarely, septarian structures also occur in claystones without concretions. In certain layers, long, branching, star-like, wedging-out cracks appear, which were later partially or completely filled with calcite. The individual crack groups are isolated from each other.
4) Desiccation polygons. Desiccation polygons are typical of dolomite and siltstone intercalations (Figs. 5A, D, 12). They were formed when the sediment surface dried out. The desiccation cracks may penetrate the sediment to a depth of up to 1.5 m (Fig. 5D). Deep cracks were observed to follow zones of weakness, i.e. previous desiccation cracks.
5) Authigenic breccias. Breccia structures are relatively rare in the succession. They are a few to a few tens of centimetres thick. The clast margins are often green due to chloritisation (Figs. 5E, G). The matrix consists of reddish-brown claystone, thus the structure must be early diagenetic.
6) Disturbed structures. Claystones and silty claystones are frequently characterised by various types of disturbed structures (Fig. 3B) connected to the inundation of previously dried sediments. The simplest is contorted bedding, with easily recognizable, often bent or overturned bed fragments (Fig. 3D). Rip-up clasts derived from dolomitic intercalations have a peculiar cloud-like appearance with blurred edges due to soddening of the clasts' margins. Plastic load structures are also common and may have been caused by differential plasticity of the beds

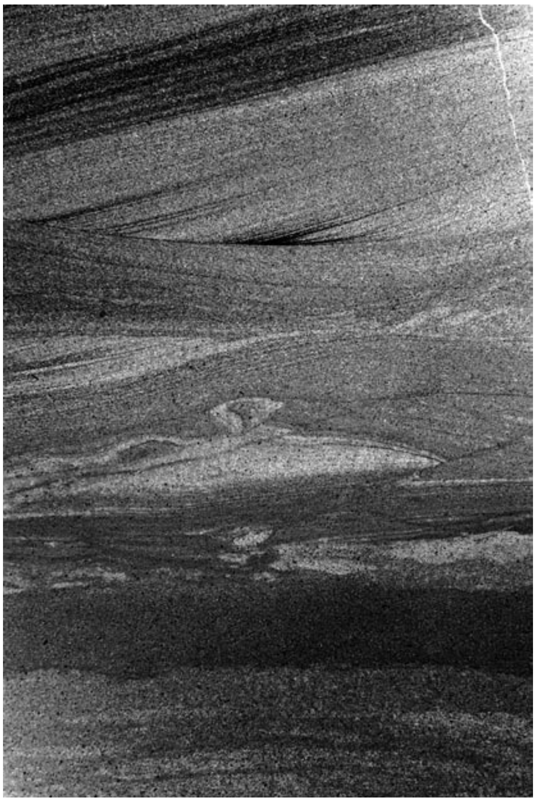

Fig. 10. Current ripples and load structures from borehole Bat-4, 998.1 m. Thin section, 1 nicol, image width 15 mm.

Fig. 11. Ripple cross-bedding in siltstone overlying claystone with a pedogenic structure. Surface of drilling core from borehole Ib-4, 646 m, image width 5 cm.

due to repeated drying and wetting during early diagenesis (Fig. 3D).

7) Pedogenic structure**.** The seemingly homogeneous typical silty claystone of the formation frequently shows a pedogenic structure in boreholes (Fig. 5F) and polished sections. The destruction of the original bedding is a result of bioturbation by roots and soil fauna, of repeated drying and wetting of the sediment, and possibly of geochemical reactions. Several transitional forms with varying levels of bioturbation exist between contorted bedding and pedogenic structures, showing a pedogenic overprint on lacustrine and lake-margin sediments.
8) Trace fossils. The trace fossils have important palaeoecological implications, so they will be dealt with separately in the section below.

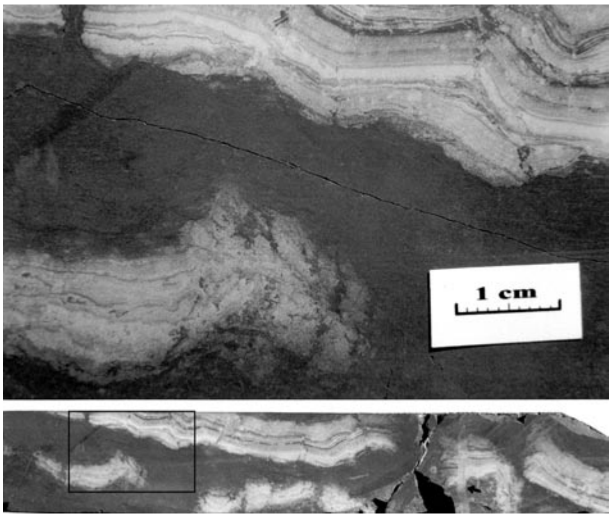

Fig. 12. Tepee structures in dolomite intercalations in the borehole Delta-3.

Ichnofossils

Systematic ichnology

Ichnogenus *Skolithos* Haldeman, 1840
Skolithos isp.

Endichnia (traces inside sediment): full relief, single, vertical, unbranched, straight, cylindrical or oval burrows; diameter 3–5 mm. Burrow fill is structureless, commonly similar to the host rock. *Skolithos* is interpreted as a dwelling (*Domichnia*) burrow made by a suspension-feeding animal.

Ichnogenus *Tigillites* Rouault, 1850
Tigillites isp.

Endichnia: full relief, single, vertical, unbranched, straight, cylindrical or poorly oval burrows with large (1–2 mm) ‘halo’; diameter 6–7 mm; fill with structureless sediments essentially identical to surrounding sediments (Fig. 13A). *Tigillites* is interpreted as a dwelling (*Domichnia*) burrow made by a suspension-feeding animal.

Ichnogenus *Arenicolites* Salter, 1857
Arenicolites isp.

Endichnia: double circle on the surface and vertical, full relief, unbranched, U-shaped, cylindrical burrows without a spreite (i.e. internal layering that fills the plane between the arms of the U), perpendicular to bedding plane. Diameter of tubes is 1–3 mm. *Arenicolites* is interpreted as a dwelling burrow (*Domichnia*) made by worm-like animals.

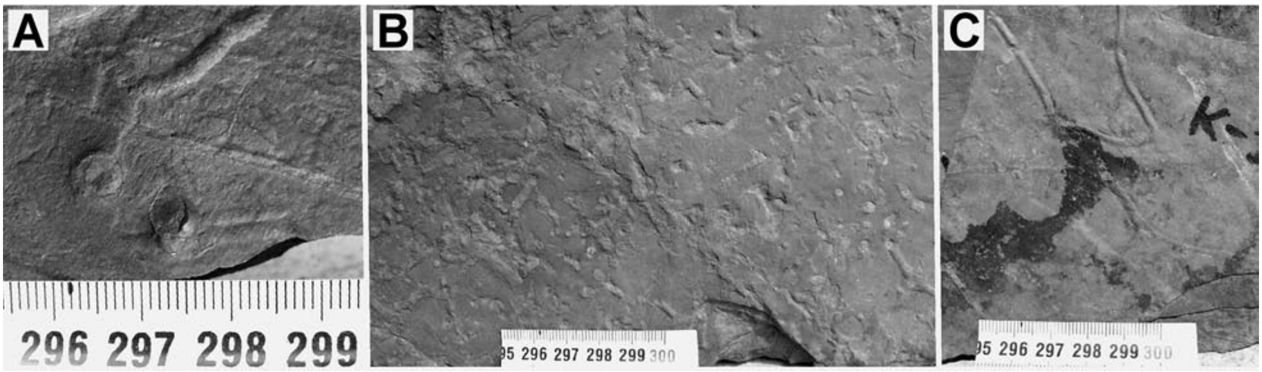

Fig. 13. Trace fossils.
A – *Tigillites* (from outcrop S-52); **B** – *Diplocraterion* (from outcrop S-53); **C** – crawling traces (from outcrop K-117).

Ichnogenus *Diplocraterion* Torell, 1870
Diplocraterion isp.

Endichnia: full relief, U-shaped, cylindrical burrows with a spreite perpendicular to the bedding plane (Fig. 13B). Diameter of tube is 2–4 mm. Distance between the two vertical parts of tube is 6–10 mm. *Diplocraterion* is interpreted as a dwelling burrow (*Domichnia*) made by an animal that adjusted its burrow either up or down in response to increased sedimentation or erosion, respectively.

Horizontal traces

1) Convex epirelief (traces on sediment): single, straight, branched, thin ridges parallel to the bedding plane. Diameter of traces is 2–5 mm, length is 5–20 cm (Fig. 13C). Infillings are the same as the host sediment. These ridges are crawling traces (*Repichnia*).
2) Convex epirelief (traces on sediment): single, straight, unbranched, thin ridges parallel to the bedding plane. Diameter of traces is 0.5–1.5 mm, length is 2–5 cm. Infillings are the same as the host sediment. These ridges are crawling traces (*Repichnia*).

Palaeoenvironmental implications

The trace fossils represent the lacustrine equivalent of the marine *Skolithos* ichnofacies (Buatois & Mángano, 2004) and an environment of relatively low-energy conditions (Pemberton et al., 1992).

The *Skolithos* ichnofacies is indicative of relatively high levels of wave or current energy. Increasing energy levels enhance physical reworking, thus obliterating the biogenic structures but preserving physical sedimentary structures. Most tracemakers found here are suspension feeders. The organisms typically construct deeply penetrating, more or less permanent domiciles (*Skolithos, Tigillites* and *Arenicolites*).

The horizontal traces indicate an environment of low-energy conditions, from moderate-energy levels in shallow waters to low-energy levels in deeper, quieter waters. Sediment deposition is negligible to moderate, but is not necessarily rapid. Characteristic organisms therefore include both suspension and deposit feeders. Burrows tend to be constructed horizontally (crawling traces) rather than vertically.

Cyclostratigraphy

The recognition of cycles is based on the alternating occurrence of four main lithofacies: sandstone, siltstone, claystone, and dolomite (dolomicrite). From a cycle stratigraphical aspect, the formation can be subdivided into three units. These were defined on the basis of the occurrence of dolomite (dolomicrite) and sandstone in the succession, because siltstone and claystone are present all over. The lower unit is devoid of dolomite intercalations, all lithofacies occur in the middle unit, whereas the upper one is characterised by the lack of sandstone layers.

Statistical analysis of the cycles showed that the theoretical cycle is a sequence made up of all rock types and contains the entire sandstone-to-dolomite succession. Because of changes within the studied formation, the definition of the modal cycles that are closer to reality and to practical applications was carried out for each of the three units separately. The ideal cycle is composed of three or four members, but commonly one of the two middle members of the sandstone-siltstone-claystone-dolomite succession does not appear. Within the ideal cycle, 2-member incomplete cycles and rhythms occur, and these are present all over the formation. In incomplete cycles, typically the lower or upper cycle member is missing; these cycles can be called incomplete at the base or at the top. The most common incomplete cycles have two members; however, these can be considered part of a bigger cycle and are consequently not considered as rhythms.

In the lower part of the succession, characteristic cycles are incomplete at the top because of the lack of dolomitic layers. In the middle part, all three types (ideal cycle, and cycles that are incomplete at the base or at the top) occur. This is the unit where ideal cycles occur most frequently; from bottom to top the number of incomplete cycles increases, while the number of cycles that are incomplete at the top decreases. In the upper unit (the upper 400–500 m), the number of ideal cycles is insignificant and the alternation of claystone/siltstone and dolomite cycle members becomes dominant. It is worth mentioning that, in some cases, cycles ending with desiccated dolomite are followed by the rock type underlying the dolomite and then by another cycle independent of the previous one. This may mean that, after the deposition of the dolomite, the same sedimentation process continued as the one preceding it. This is characteristic of symmetrical cycles.

The formation cannot be dated exactly; therefore part of the 'classical' investigations is impossible to be carried out (Weedon, 2003). Flora and fauna that can be used for dating are missing in the formation, thus the time required for the accumulation of cycles/rhythms can not be determined; only estimations are possible.

Facies interpretation and palaeogeographical conditions

Jámbor (1964) was the first to give a detailed description of the formation and to interpret it as a lacustrine sediment. Mineralogical, petrographical, geochemical and sedimentological characteristics of the formation revealed by further studies referred to deposition in a shallow, alkaline lake under arid/semi-arid climatic conditions.

The palaeogeographical reconstruction (Fig. 3C) shows that the provenance area was dominated by the Lower Carboniferous granites and the Lower Permian Gyűrűfű Rhyolite, while metamorphic rocks were subordinate. The lacustrine basin received only fine-grained sediments, while in the surrounding areas coarser-grained deposits from ephemeral streams accumulated (Cserdi Formation). The only – and very local – coarse input to the basin is represented by the polymictic basin-margin fanglomerates interfingering with the claystones/siltstones. Sediment types, structures and trace fossils all refer to an upwards decreasing transportation energy. The connection between the main textural and structural characteristics is shown in Table 1.

Lithofacies analysis has shown that the major part of the succession was deposited in a playa basin, but rather on the playa mudflat and not in a playa lake in a strict sense. Lake sediments are represented by laminated and ripple-marked/flaser-type cross-laminated claystones and siltstones, and by massive dolomites; trace fossils include crawling traces and burrows. Occasional storms oxygenated the lake water and created the littoral sedimentary structures. Partial or complete drying out of the lake commonly occurred after the formation of carbonate mud by evaporation. Periodic fluvial influx is recorded by cross-bedded sandstones and unsorted sandstones consisting of angular grains of up to pebble size. The very few greyish-green, reduced intercalations suggest climatic events with more precipitation (as described, for example, from the Middle Permian succession in France; Schneider et al., 2006) and/or the ponding of

Tab. 1. Textural and structural characteristics of the Boda Claystone Formation.

Features/structures	Sediment type					
	conglomerate	sandstone	siltstone	silty claystone to clayey siltstone	claystone	dolomicrite
erosional basal contact	+	+	++			++
massive structure	+			++		
horizontal stratification		+	+		++	++
ripple cross-bedding		++	++			+
disturbed structures				++	+	+
pedogenic structures				+++	+	
authigenic breccia			+	+	+	+
desiccation features		+	+++	+	+	+++
calcite- (and albite-) filled cavities			+	+++	+	+
trace fossils		+	+	+	?	+

Legend: + present; ++ common; +++ typical.

water. Fenestral and stromatolitic structures represent the repeated appearance of a playa mudflat facies covered by a microbial mat. The numerous cavities were supposedly formed by gases produced by the decay of organic matter.

The silty claystones, which constitute the major part of the succession, lost their primary structures due to pedogenic physical, chemical and biological processes, and indicate prolonged subaerial periods with soil formation and only ephemeral inundations. The presence of pedogenic carbonate concretions supports the interpretation of an arid climate and refers to a relatively shallow groundwater table. Drying-out events shown by desiccation cracks and authigenic breccias can be traced all over the succession.

The occurrence and frequency of trace fossils indicates that during periods of increased evaporation (dolomite layers) as well as during more humid climate intervals (ripple-marked siltstones and sandstones) the abundance of burrowing organisms decreased. The relatively high abundance of burrowing organisms refers to an environment rich in organic matter; this is also supported by the high frequency of fenestral structures. The various facies are ordered into small-scale (low-rank) sedimentary cycles showing a shallowing-upward trend and the growing influence of aridity and subaerial exposure.

According to the illite and chlorite crystalline index and to the vitrinite reflectance measured in a reduced intercalation, the formation was affected by near-anchizone deep diagenetic impact (max. 200–250°C) (Árkai et al., 2000). In the western part of the distribution area, the burial depth was probably smaller, since also analcime, the precursor mineral of late diagenetic albite, has been preserved there.

Though marginal successions of the formation are only known from the North and the East, it is beyond doubt that the original extent of the formation was considerably smaller than that of the under- and overlying sediments. In combination with the extreme thickness of the BCF, this indicates the presence of boundary faults that were active during the deposition of the formation (Fig. 3C), tentatively attributed to the dying out continental rifting indicated by the underlying rhyolitic rocks (Fazekas et al., 1981). Subsidence and basin formation were eventually driven by crustal reorganisation and re-equilibration following the compressional phases of the Variscan orogeny (Vozárová et al., 2009). The surroundings of the playa basin had a moderate relief, a consequence of long ongoing denudation of the crystalline basement.

As the BCF was deposited in a closed basin of relatively minor extent, possibilities for correlating the formation are limited. Within the present-day Pannonian Basin (Alcapa, Tisza and Dacia Units), no similar coeval sediments are known. Correlation with areas forming part of the European platform is hindered by the fact that the controlling processes of the postorogenic evolution of the Variscan fold-and-thrust belt were very different from those in the foreland basins (McCann et al., 2008). The impact of tectonics on these areas will therefore be difficult to compare. However, the sedimentary features of the BCF indicate the same aridification of the climate of Pangaea as do other Middle Permian playa sediments that were also deposited in isolated intramontane basins in the Variscan foreland (e.g. in the Lodève Basin: Schneider et al., 2006).

Conclusions

The Boda Claystone Formation was deposited in a subsiding basin on the southern margin of the Permian Europe. It is underlain by an extensive rhyolitic volcanic succession (Gyűrűfű Rhyolite) that indicates continental rifting.

The intramontane basin with playa lakes developed under arid climatic conditions. The major part of the formation is built up of sediments deposited in a playa mudflat, with intercalations of lacustrine and fluvial origin.

The source rocks were granite and rhyolite, so that a 'Lake Natron-type' chemical environment formed.

The oxidation state of iron, the desiccation cracks, the occurrence of analcime and its diagenetic form albite all reflect an arid depositional environment.

The cycles of the succession were controlled by climatic changes.

Due to burial (4–6 km), the sediment turned into claystone (silty claystone, clayey siltstone, albitic claystone, albitolite). The claystone body was affected by the Cretaceous and Neogene orogenic movements and became tectonised to various extents.

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