

Meiofauna, trace metals, TOC, sedimentology, and oxygen availability in the Late Miocene sublittoral deposits of Lake Pannon

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Abstract The Late Miocene fine-grained deposits have been investigated in the Vienna Basin to attest oxygen availability for infauna and epifauna in the sublittoral of the long-lived Lake Pannon. A clay and fine silt of the deeper lacustrine facies of a bay passed vertically into a silty clay, silt, and fine sand rhythmic deposition reflecting successive progradation of brackish prodelta to distal delta front colonized by a dense benthic population. A fully oxygenated environment is supposed in the *Congeria subglobosa* Beds and prodelta accentuated by ichnofauna, ostracods, and abundant in taxa and specimens, low total organic content, and trace elements concentration. A limited anoxic event caused by temporarily worsened circulation has been detected in non-calcareous greyish-blue homogenous clay with a noticeable high concentration of Ni, Co, and Pb coupled with absence of fossils, bioturbation, and low total organic carbon content.

Keywords Ostracoda · Thalassinidean burrow · *Congeria subglobosa* · Lake Pannon · Anoxia

Introduction

The Late Miocene deposits and fauna of Lake Pannon (Central Europe) reflect the existence of a large, long-lived, brackish to freshwater lake that was formed about 11.6 Ma inside the Carpathian arch (Magyar et al. 1999; Harzhauser and Piller 2007). The depositional systems of Lake Pannon are very heterogeneous, and are represented by alluvial and fluvial facies, ephemeral lake, swamp, and subaquatic delta plain deposits passing continually into offshore pelitic facies (Harzhauser and Tempfer 2004; Kováč et al. 2005). Palaeontological studies have examined the different ecological parameters which could have played a role during the establishment of the aquatic biotopes—salinity (e.g. Krstić 1971; Pipík 1998), stratified water column and alkaline reaction (Harzhauser et al. 2007), and water depth (Juhász and Magyar 1992; Cziczzer et al. 2009).

Oxygen availability should be a significant factor for the evolution of the benthic endemic fauna (Martens 1994) and is assumed to be important in shaping the sedimentary facies and biofacies of Lake Pannon. Harzhauser and Mandic (2004) supposed a low-energetic hypolimnion environment poor in oxygen with supersaturated sulfidic interstitial waters settled by *Congeria subglobosa*. Magyar et al. (2006), following the sedimentary facies, ichnofacies and mollusc biofacies, concluded that the oxygen deficiency was a local phenomenon caused by a high organic input and/or a salinity-induced stratification.

In this paper, we analyse the Late Miocene sublittoral deposits with *Congeria subglobosa*, known as *Congeria subglobosa* Beds (CSB), which are widely distributed in Lake Pannon forming the local populations of this bivalve from a period of maximal flooding. The CSB is known from many sites in the Vienna Basin (e.g. Harzhauser and Mandic 2004; Pipík 2007; Pokorný 1952), but nowadays

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only the outcrop in Gbely (Fig. 1) exposes a sedimentary record suitable for a sedimentological, palaeontological, and geochemical study to demonstrate oxygen availability in the environment.

Geological setting and stratigraphy

The outcrop Gbely brickyard is situated approximately 1.2 km SSE from the centre of the town of Gbely in an abandoned quarry in the Vienna Basin (Fig. 1; 48°42′26.33″N; 17°07′12.74″E). The lithofacies studied is a part of the lacustrine deltaic succession belonging to the Záhorie Member of the Bzenec Formation deposited during the Late Miocene (Vass 2002).

Articulated shells of *C. subglobosa* attest an autochthonous position of this bivalve within a clay deposit and allow us to attribute the succession to the regional Pannonian zone E sensu Papp (1951) (Figs. 2, 3). This zone is further confirmed by the ostracods *Cyprideis obesa* (Reuss 1850), *C. heterostigma* (Reuss 1850), *Hemicytheria folliculosa* (Reuss 1850), *H. reniformis* (Reuss 1850)

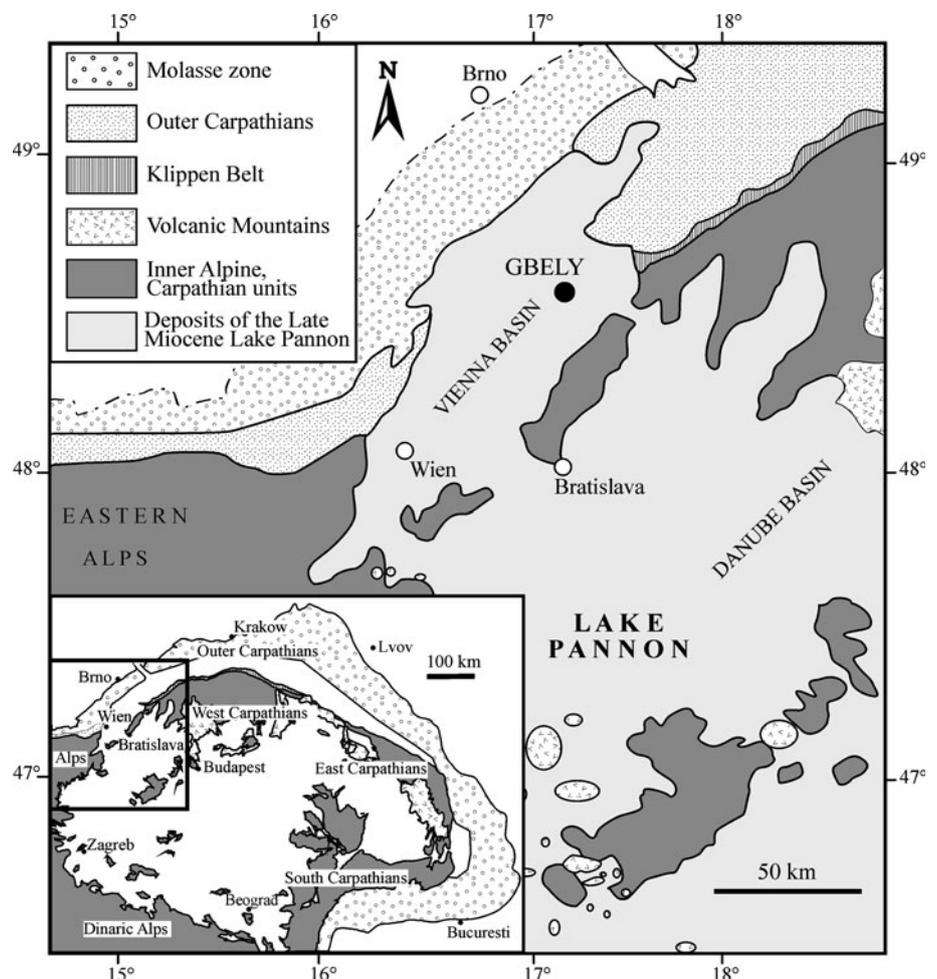
(Jirřek 1985). Within zone E, the outcrop is biostratigraphically coeval but not synchronous with clay deposits exposed in Hengersdorf (Austria) at which the magnetostratigraphic measurements correspond to the interval C5n (11.04–9.78 Ma) (Magyar et al. 2007).

Methods

Palaeontological methods

Two samplings for micropalaeontological objectives were carried out in the Gbely outcrop. All samples were naturally dried in the laboratory and successively washed through a sieve mesh 0.09 mm wide. Twenty-five samples weighing 1 kg and labelled 1M–25M were taken along the outcrop (0.0–23.0 m) for the study of taxonomy, species composition and distribution of Ostracoda. Forty samples labelled as 1G–40G weighing 200 g were taken from 0.0 to 11.5 m of the clay-prevailing sequence for quantitative micropalaeontological, trace element (TE) and total organic carbon (TOC) analyses. A total of 150 g of

Fig. 1 Geological map of Central Europe and geographical position of the studied section Gbely in the Vienna Basin (Slovakia)



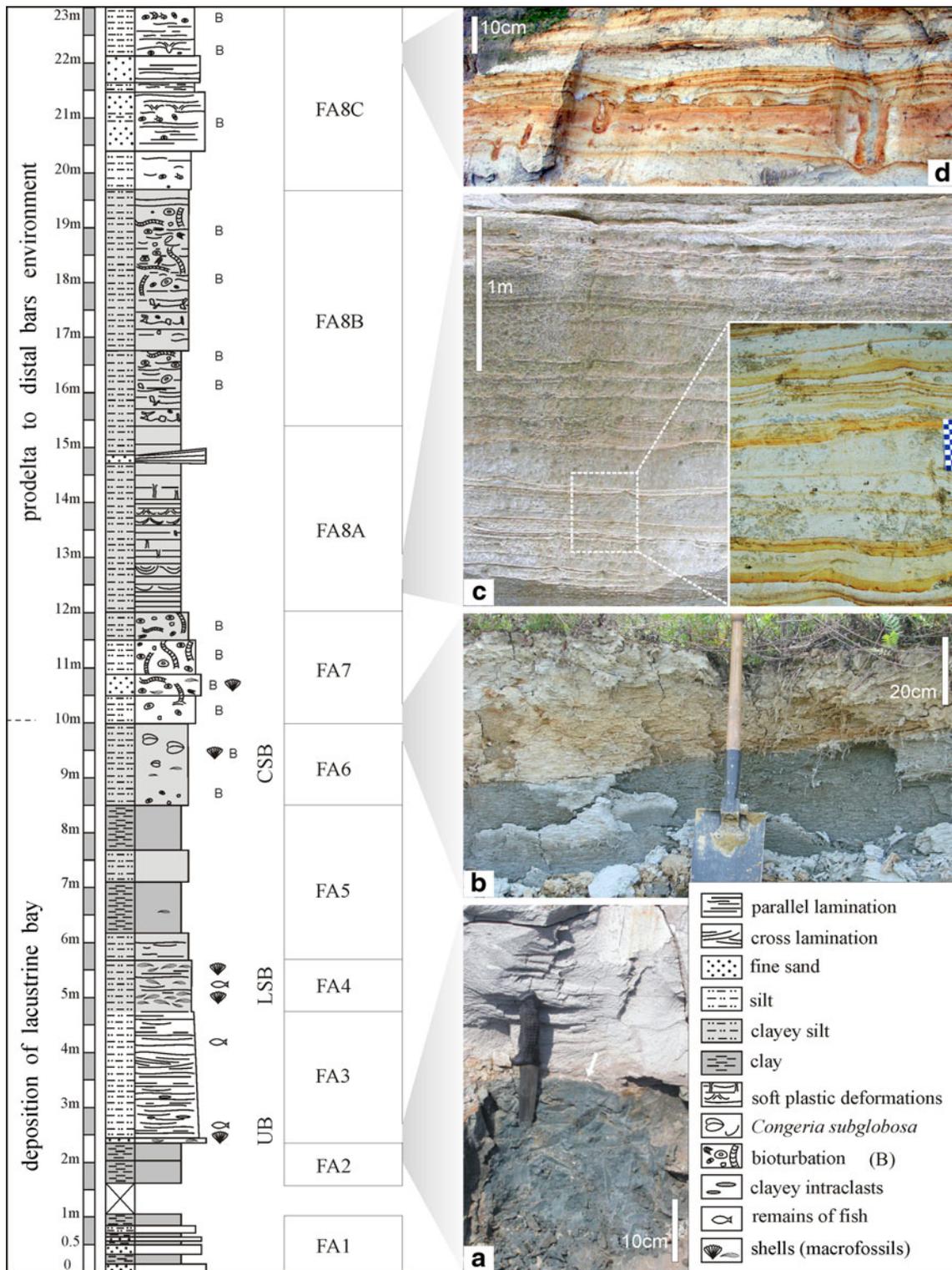


Fig. 2 Sedimentary facies associations at the outcrop Gbely with biostratigraphically and ecologically important beds in the Vienna Basin. **a** Sharp, slightly erosive contact (arrow) between non-calcareous greyish-blue clay and thick-graded sandy and silty bed with macrofauna shells and carbonized macroflora detritus at the base. **b** Contrast interface between the clayey silty *Congeria subglobosa* Beds and the overlapping massive, fine-grained medium- to fully

bioturbated sand and silt. **c** Rhythmic silty clay, silt and fine sand succession of a prodelta environment (enlarged section on the right; a black field on the scale corresponds to 1 cm). **d** Isolated bioturbated horizons coupled with conical sedimentary structures. *CSB* *Congeria subglobosa* Beds; *LSB* *Limnocardium schedelianum* Beds; *UB* *Unio* bed; *FA* facies association

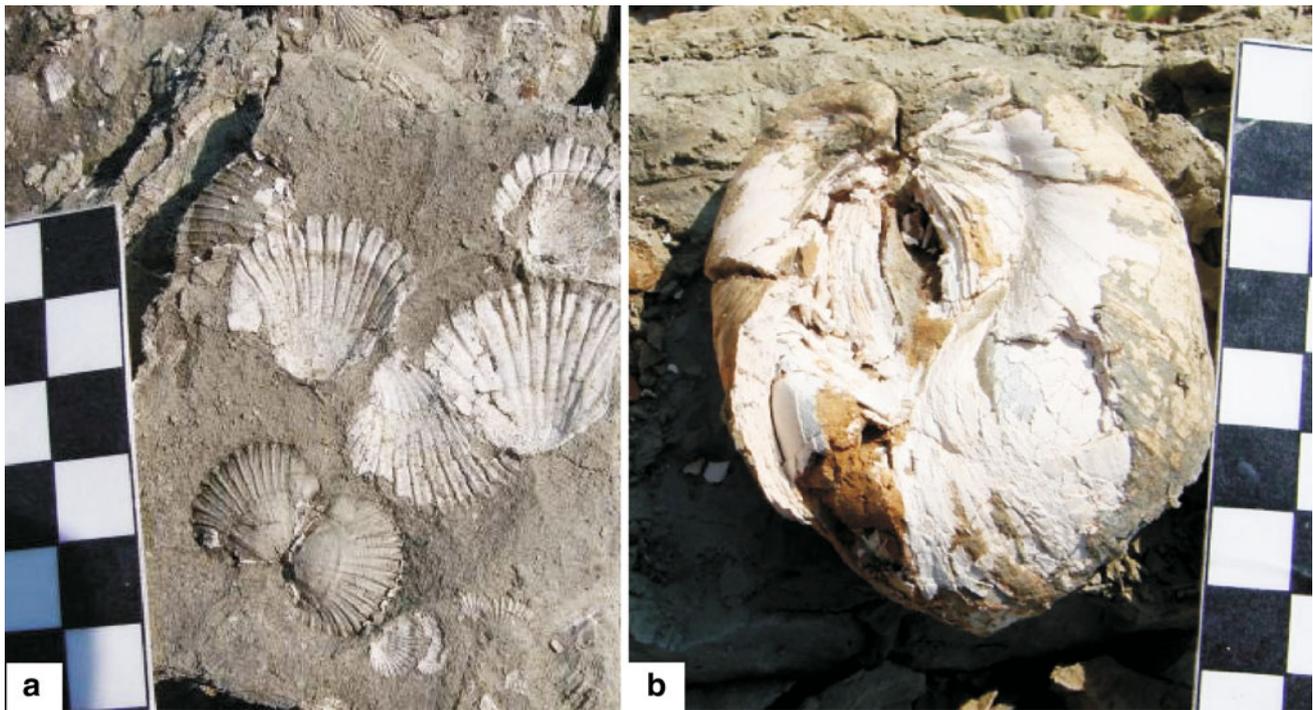


Fig. 3 Macrofauna. **a** *Limnocardium schedelianum*. **b** *Congeria subglobosa*. A black field on the scale corresponds to 1 cm

naturally dried sediment from the samples 1G–40G was washed and used for quantitative micropalaeontological analyses. Only adult and juvenile ostracod valves, complete and equal or greater than half of the valve were taken into account.

Geochemical methods

Ten grams of original deposit of the samples 1G–40G was dried (105°C), then homogenized and used for TREE (Pb, Cd, Cr, Cu, Co, Ni) and TOC analyses to approve redox conditions (Skei et al. 1996; Schaller et al. 1997; Cohen 2003).

For TOC measurements, each sample (0.0500 g) was dried at 110°C and loaded in a C—MAT 5 500 detector (Ströhlein, Austria). The accuracy of analytical results was controlled by Standardprobe Basalt BM (ZGI, Germany). The standard deviations for TOC concentrations in the range of 0.1–1.0 and 1.0–3.0% were 0.08 and 0.07%, respectively.

For trace metal determination, 1 g of a sample was dissolved in an acid mixture (HNO₃, HF, HClO₄) using an open system. Solid residue was fused in a Pt-crucible by a melt mixture of Na₂CO₃ + Na₂B₄O₇.

The contents of Co, Cr, Cu, Ni, and Pb were measured by a Perkin-Elmer 1100 atomic absorption spectrometer (Norwalk, CT, USA) equipped with an acetylene-air flame.

The spectrometer was provided with a deuterium-based background corrector.

The content of Cd was measured by a Perkin-Elmer 3030 atomic absorption spectrometer (Norwalk, CT, USA) equipped with an HGA 600 graphite furnace and an AS-60 autosampler. The spectrometer was provided with a Zeeman-based background corrector. For measurements, pyrolytically coated graphite tubes (Perkin-Elmer, USA) were used exclusively and injection of a sample solution (20 μl) was followed by modifier solution (10 μl of 2% NH₄H₂PO₄).

The accuracy of analytical results for trace metals in samples was checked by certified standard reference materials GBW 07 304 Chinese Stream Sediment (Beijing, China) and Kaolin KK (Kutná Hora, former Czechoslovak Republic). A relative standard deviation (corresponding to four independent replicates) varied in the range of 1–5%.

Results

Sedimentary facies associations

The analysed sediments are of subaqueous origin and were formed exclusively by fine-grained sedimentation of clay, silt, and very fine sand. The lower part of the sequence (0.0–10.0 m) has a prevalence of clayey sedimentation

with variable abundance of micro- and macrofauna, and relatively poor occurrence of bioturbation. A sharp transition to the upper part (10.0–23.0 m) with rhythmic sedimentation of clay, silt and fine-grained sand is accentuated by the occurrence of ichnotaxa and soft-sediment deformation structures.

On the basis of lithology, primary and/or secondary sedimentary structures and presence of fauna, eight types of sedimentary facies associations (FA) have been recognized in the outcrop (Fig. 2):

Facies association 1 (FA1): Intercalations of thin sand beds with sharp lower contacts and calcareous light-grey clay beds (0.0–1.0 m). A taphocoenosis composed of brackish *Cyprideis heterostigma*, *Cypria abbreviata* (Reuss 1850), *Loxoconcha granifera* (Reuss 1850) and *Hemicytheria* sp., and rare freshwater *Darwinula stevensoni* (Brady and Robertson 1870), *Cyclocypris* sp., *Ilyocypris* sp.

Facies association 2 (FA2): Weakly calcareous grey-brown and non-calcareous greyish-blue homogeneous clay (1.7–2.4 m), barren of fossils and bioturbation. This succession occurs only in the lower part of the studied section (Fig. 2a). Observed stratification within the clay is distinguished as a result of differences in colour.

Facies association 3 (FA3): Upward-fining calcareous sequence of the graded sand and laminated silt (2.4–4.8 m). This sedimentary body has a sharp and slightly erosive lower contact (Fig. 2a) to FA2. The base is formed by a thin (5–10 cm) violet sandy horizon with disarticulated, complete and broken shells of *Unio*, *Melanopsis*, and carbonized macroflora detritus. A remaining part of FA3 is formed by crude laminated dark brown silt. A lower interval (90 cm thick) of this laminated silt unit contains small rounded clayey intraclasts and abundant fish bones, scales, and teeth. A less distinguishable, 20-cm-thick, low-angle cross-stratified interval is observed in the middle part of the same silty unit. The upper boundary of FA3 is not sharp and a laminated silt unit continually passes upwards to a clayey silt (=Facies association 4). An association *Caspiocypris fahrioni* (Turnovsky 1954) and *Cyprideis obesa* occurs only in the FA3 (sample 8 M).

Facies association 4 (FA4): A high concentration of *Limnocardium schedelianum* shells in concave and convex position, articulated and disarticulated is documented from a grey clayey silt (4.8–5.7 m) (Fig. 3a). This unit shows an indistinctive lamination formed by shell accumulation. Abundant brackish ostracods *Amplocypris recta* (Reuss 1850), *Cyprideis heterostigma*, *C. obesa*, *Hemicytheria folliculosa*, *Loxoconcha granifera*, and *Pontoniella prochazkai* (Pokorný 1955) were found.

Facies association 5 (FA5): A predominantly homogeneous blue-grey and brown, weakly calcareous clay and silty clay (5.7–8.5 m) lacks any bioturbation and rarely contains small fragments of *Limnocardium* and ostracod

carapaces with pyrite inside. Sediments show layering due to differences in both colour and grain size. The ostracod association is similar to that of FA4, enriched by *Amplocypris abscissa* and *Lineocypris hodonensis* (Pokorný 1952) and this association repeats up to the top of the sedimentary sequence.

Facies association 6 (FA6): Brown-grey clay and silty clay with *Congeria subglobosa* (8.5–10.0 m), which corresponds to our CSB. The valves of this massive bivalve are closed (Fig. 3b), frequent, and irregularly distributed in the deposit. Traces of the infauna, which settled this muddy environment, are attributed to the thalassinidean burrows (see “*Ichnofossils*”). The ostracod association of the CSB is the most diverse with 11 brackish species: *Amplocypris abscissa*, *Cypria abbreviata*, *Cyprideis heterostigma*, *C. obesa*, *Euxinocythere lacunosa* (Reuss 1850), *Hemicytheria folliculosa*, *Lineocypris granulosa* (Zalányi 1959), *L. hodonensis*, *Loxoconcha granifera*, *Pontoniella prochazkai* (Pokorný 1955), and *Typhlocypris fossulata* (Pokorný 1952).

Facies association 7 (FA7): Massive, fine-grained medium to fully bioturbated ocherous sand and silt (10.0–12.0 m) with upward decreasing grain size. The lower bed-contact with the CSB is sharp (Fig. 2b). The primary sedimentary structures and interfaces were probably destroyed by heavy bioturbation. The bedding interfaces have been specified only roughly by observed differences in grain size of the individual units. The very abundant bioturbation traces, variable in size are recognized as thalassinidean burrows (see “*Ichnofossils*”). The brackish ostracod association is almost identical with the association of the FA6.

Facies association 8 (FA8): Light grey silty clay, silt and fine sand succession (12.0–23.0 m) shows layering due to differences in both colour and grain size. Very thin rhythmites (0.5–7.0 cm in thickness) of silt/sand and silty clay are the most noticeable feature. The entire succession shows an upward coarsening trend in grain size with a variable occurrence of ichnotaxa and soft deformation structures. The primary and secondary sedimentary structures and interfaces in this FA are highlighting and well distinguishable by ocherous stains. This ocherous or limonitic pigmentation of sandy and silty sediment is considered as a result of post-depositional ground water flows and it was concentrated in preference to the primary lithological and grain-size interfaces as well as it follows a running of the sedimentary structures.

This rhythmic succession is divided into three sections: FA8A: Lamination of silty clay, silt and very fine sand (12.0–15.4 m) is disrupted by soft-sediment deformation structures as a result of escaping pore fluids (Fig. 2c, see Soft-sediment deformation structures). Bioturbation within the sediment is rare and a scattered lithified pinching sandy

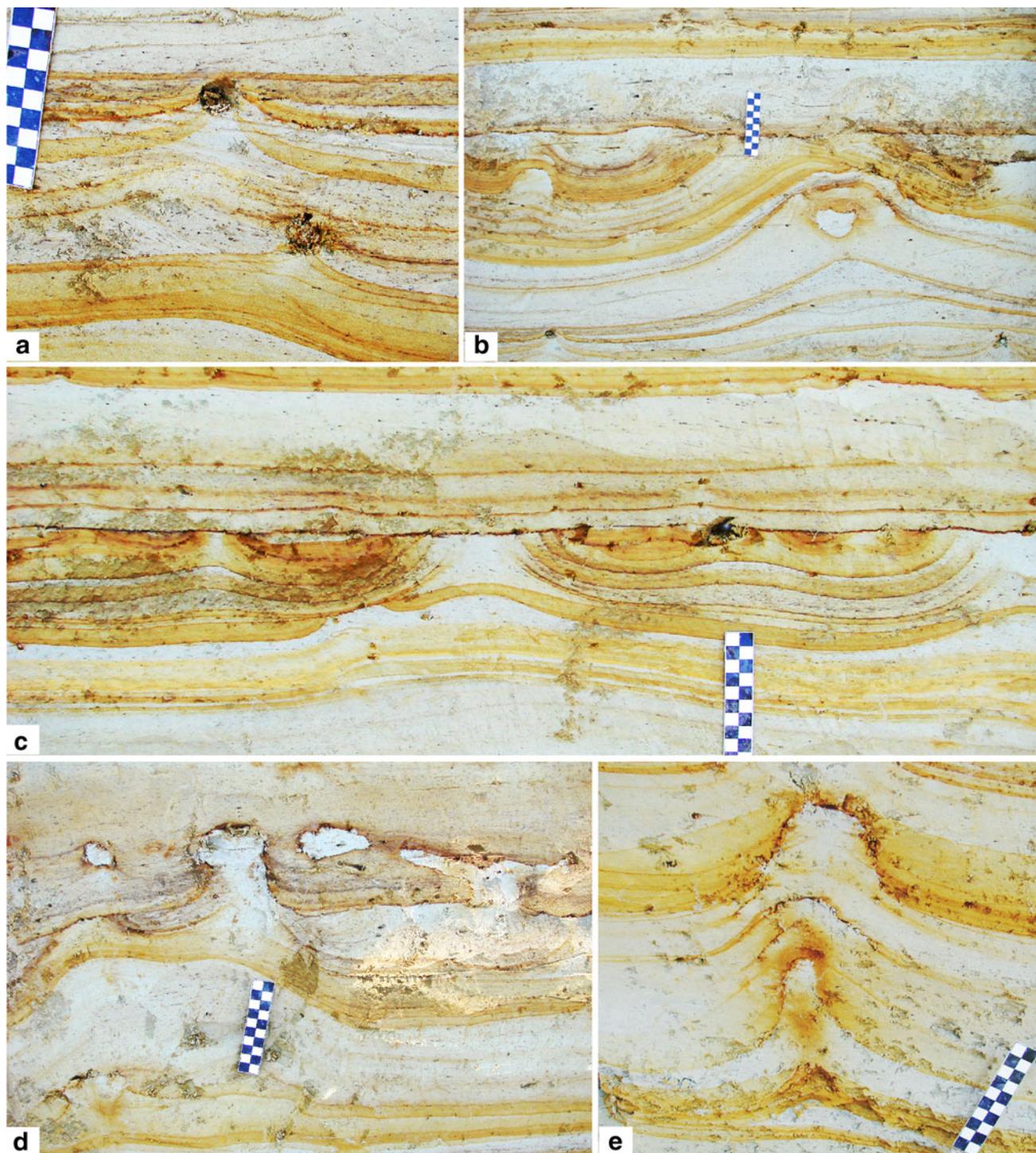


Fig. 4 Inorganically initiated soft-sediment deformation structures (Facies association 8A). **a** Small upwarping cusps. **b** Subvertical irregular conduits, circular in cross sections, caused by fluid-

upwelling. **c** Concave-upward dish-and-pillar structures. **d** Sedimentary intrusions. **e** The largest-scale fluid-upwelling structures. A black field on the scale corresponds to 1 cm

bed with lamination is present. This bed has a graded base and both, a lower and upper bed contact is sharp.

FA8B: Silty part (15.4–19.7 m) with well-developed thalassinidean ichnofossils (see “[Ichnofossils](#)”). Bioturbation becomes upwardly more abundant and individual parts

of the sediment are entirely disturbed. An ostracod fauna is missing in these strongly bioturbated intervals.

FA8C: A sandy and silty material is dominant in the uppermost part (19.7–23.0 m) (Fig. 2d). This section is distinguished by occurrence of isolated bioturbated

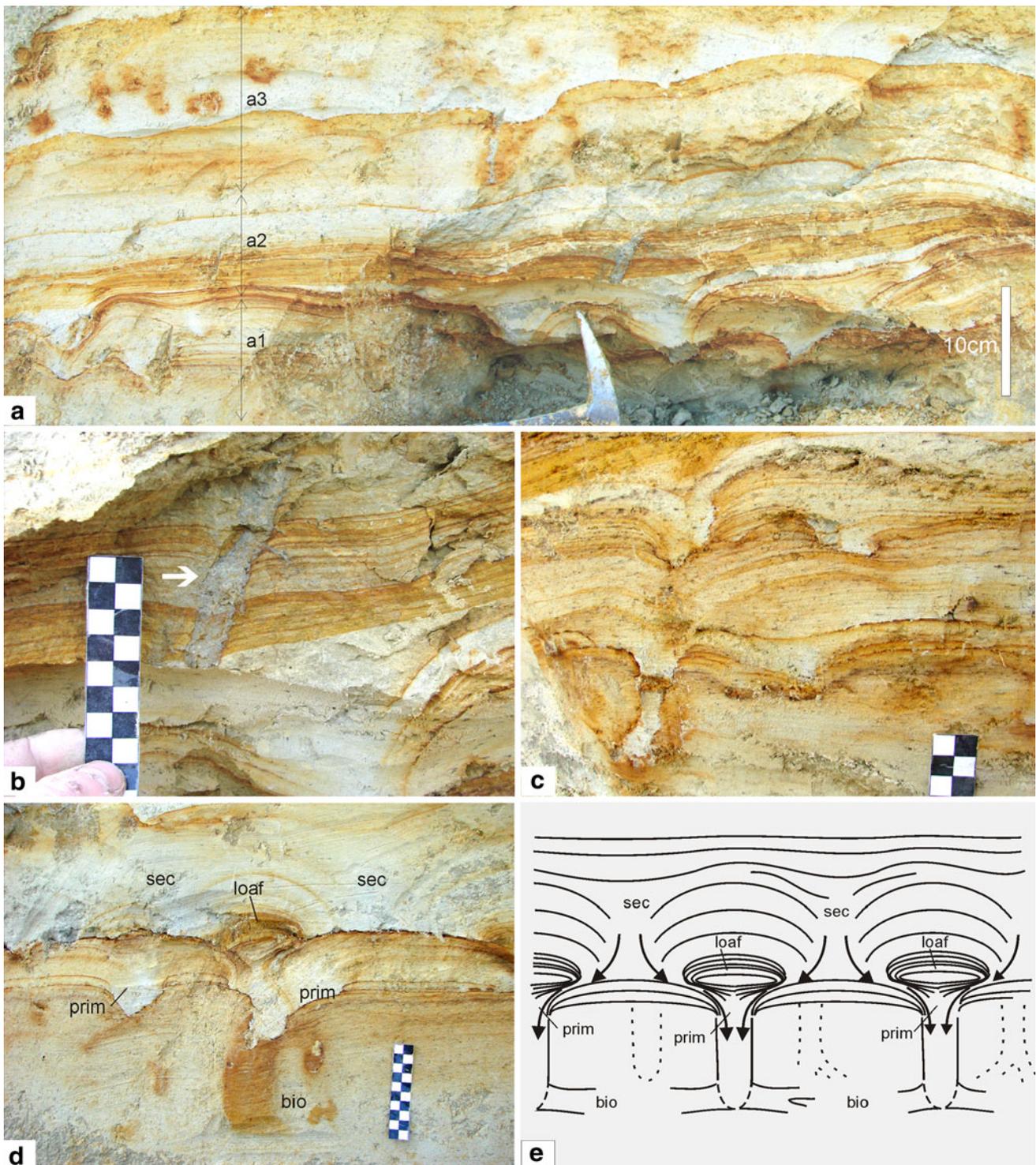


Fig. 5 Organically initiated soft-sediment deformation structures (Facies association 8C). **a** Vertical changes in bottom colonization: *a1* Conical downwarped V-shaped sedimentary structures related to the burrow cavity; *a2* non-bioturbated, rhythmic thin lamination overlapped conical collapse structures reflecting a colonization window during a period of rapid deposition; *a3* recolonization of the bottom. **b** Detail of escaping trace (*arrow*) within a buried horizon.

c Conical downwarped sedimentary structures. **d** Complex of bioturbations (*bio*) and collapse sedimentary structures form system of primary (*prim*) and secondary (*sec*) cones and “loaf-like” (*loaf*) structures. **e** Schematic cartoon showing a formation of conical collapse structures (shortcuts the same as on Fig. 5d). A black field on the scale corresponds to 1 cm

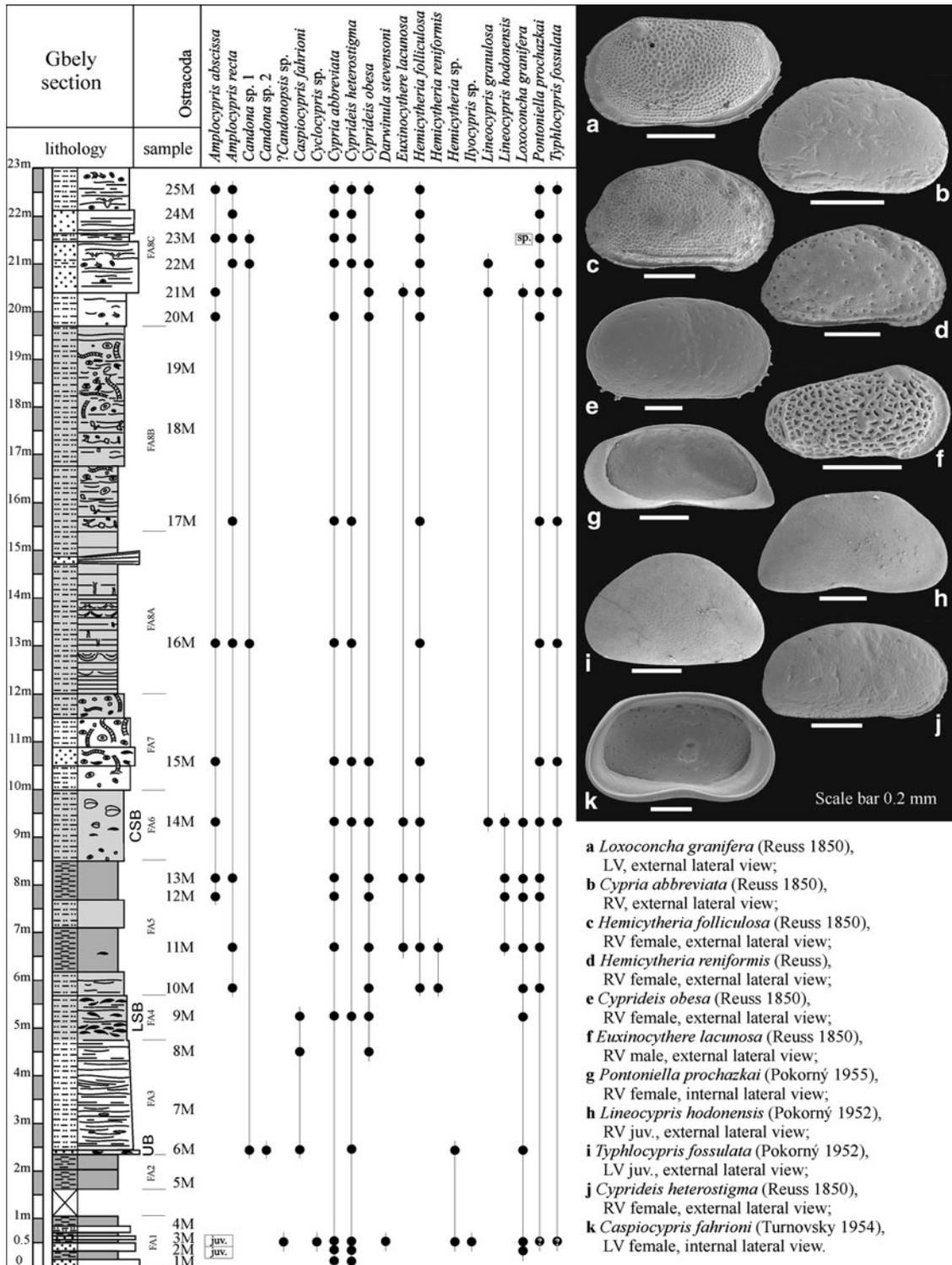


Fig. 6 Log of the Gbely section and distribution of the Ostracoda. Ostracods of the *Congerina subglobosa* Beds (a–i) and of the other beds (j, k). RV Right valve, LV left valve, juv. juvenile. For explanation see Fig. 2

horizons with thalassinidean burrows (see “Ichnofossils”) and simple vertical shafts that are often coupled with a presence of conical sedimentary structures (see “Soft-sediment deformation structures”).

The ostracod fauna is almost identical with that brackish observed from FA4 to FA7, but freshwater *Candona* sp. 1 reoccurs at base (FA8A) and top (FA8C) of this succession.

Soft-sediment deformation structures

Occurrence of soft-sediment deformation structures is strictly limited to FA8 (12.0–23.0 m), mainly sections FA8A and FA8C, where these deformations influenced the alternation of the multilayer heterolithic deposition of sand, silt and clay.

With respect to processes that generate a formation of such deformation, two categories were distinguished. The first category comprises structures with origins that can be explicitly attributed to inorganic processes as a result of liquefaction–fluidization. The second category includes collapse structures with origins conditioned by animal activity and are attributed to ichnotaxa (see “[Ichnofossils](#)”).

Inorganically initiated soft-sediment deformation structures

The small-scale soft deformations are formed by upwarping cusps or small siphons, usually not exceeding 1–2 cm in height and they have been found unequally in slightly and non-bioturbated sequences (Fig. 4a).

The medium to large-scale soft deformation structures have various levels ranging from gently deformed lamination and small pipes to moderately strong concave-upward dish-and-pillar structures, conduits and sedimentary intrusions (Fig. 4b, c, d).

The largest-scale fluid-upwelling structures are represented by vertical or subvertical conduits with irregular circular cross sections. Their size varies from 10 to 40 cm in height and up to 5 cm in diameter. A source of the conduits is found in silty or sandy beds that are limited at the base and at the top by low-permeable clayey silty beds. The lower feeding part of the conduits has an upward narrowing conical morphology (Fig. 4e).

The majority of these water-escape conduits show relatively simple forms but heavily deformed their surroundings with lamination folded upward close to the conduit borders (Fig. 4b, c). However, the vertical development of the conduits is variable and irregular. Therefore, different sections offer various views of structure complexity combined with conduit and plastic or brittle deformation (folded or broken laminae) of the ambient sediment.

Organically initiated soft-sediment deformation structures

This category of deformation structures includes the conical downwarped V-shaped sedimentary structures that can be attributed to the collapse of sediment into cavities created by animals (e.g. Bromley 1996; Buck and Goldring 2003).

The investigated structures are variable in size from a few cm to about 20 cm or more in diameter and about 10 cm in height. With respect to the morphology, the majority of these collapse structures comprise a funnel-shaped vertical zone of deformation, which widens uniformly upward above the cavity (Fig. 5a, b, c, d, e) (see also Buck and Goldring 2003). Sediment laminae within the grasp of the deformation zone are drawn down in a series of inverted, mainly symmetrical cones. The deformation zone lies symmetrically on both side of the vertical axis through the centre of the cone and intensity of deformation decreases with increasing vertical and horizontal distance above the cavity (Fig. 5a, c).

Whereas primary cones are induced by collapse of sediment into cavities, secondary cones (Fig. 5d, e) are in straight sequence to primary cones and they arise as a result of the collapse of sediment into spaces released by primary collapses. The secondary cone is connected to several primary cones and it is usually larger than the primary cones. Between adjacent secondary cones and together on the top of primary collapse, the “loaf-like” structures are often developed (Fig. 5d, e). They have usually symmetrical distribution on both side of the vertical axis through the centre of primary cones and relevant cavities. These loaf-like structures represent relicts of primarily laminated sediment and their origin is related to the formation of secondary conical collapse structures.

Ostracoda

Twenty-one ostracod species, of which only ten were frequent, were recognized throughout the outcrop analysed. Ostracod barren units were found in the greyish blue clay (FA2), the cross-stratified silt (FA3 from 3.5 to 4.0 m) and in the heavy bioturbated silt (FA8B from 17.0 to 19.0 m) (Fig. 6). The valves are white, opaque, chalky, seldom translucent, frequently broken; pyritized carapaces occurred in the samples 11M and 13M. The ornamented taxa, mainly *Hemicytheria*, show the solution holes, classified as phenon S as a result of digestion sensu Maddocks (1988). The surface of these valves is almost smooth (*Hemicytheria*), with abraded margins, broken spines (*Cyprideis*, *Loxoconcha*) and enlarged pore canals probably as a result of their mechanical transport or longer exposure before final burial (Kontrovitz 1967; Kaesler et al. 1993). On a generic level, the fauna is composed of the extant brackish *Cyprideis*, *Euxinocythere*, *Loxoconcha* and fossil paratethyan genera *Lineocypris*, *Hemicytheria*, *Amplocypris*, *Caspiocypris*, *Typhlocypris*, and *Pontoniella*. *Cypria* spp. are freshwater species tolerating mesohaline conditions (Meisch 2000), but fossil *C. abbreviata* and *C. dorsoconca* Krstić 1975 from Lake Pannon are associated with the above-mentioned brackish genera. The

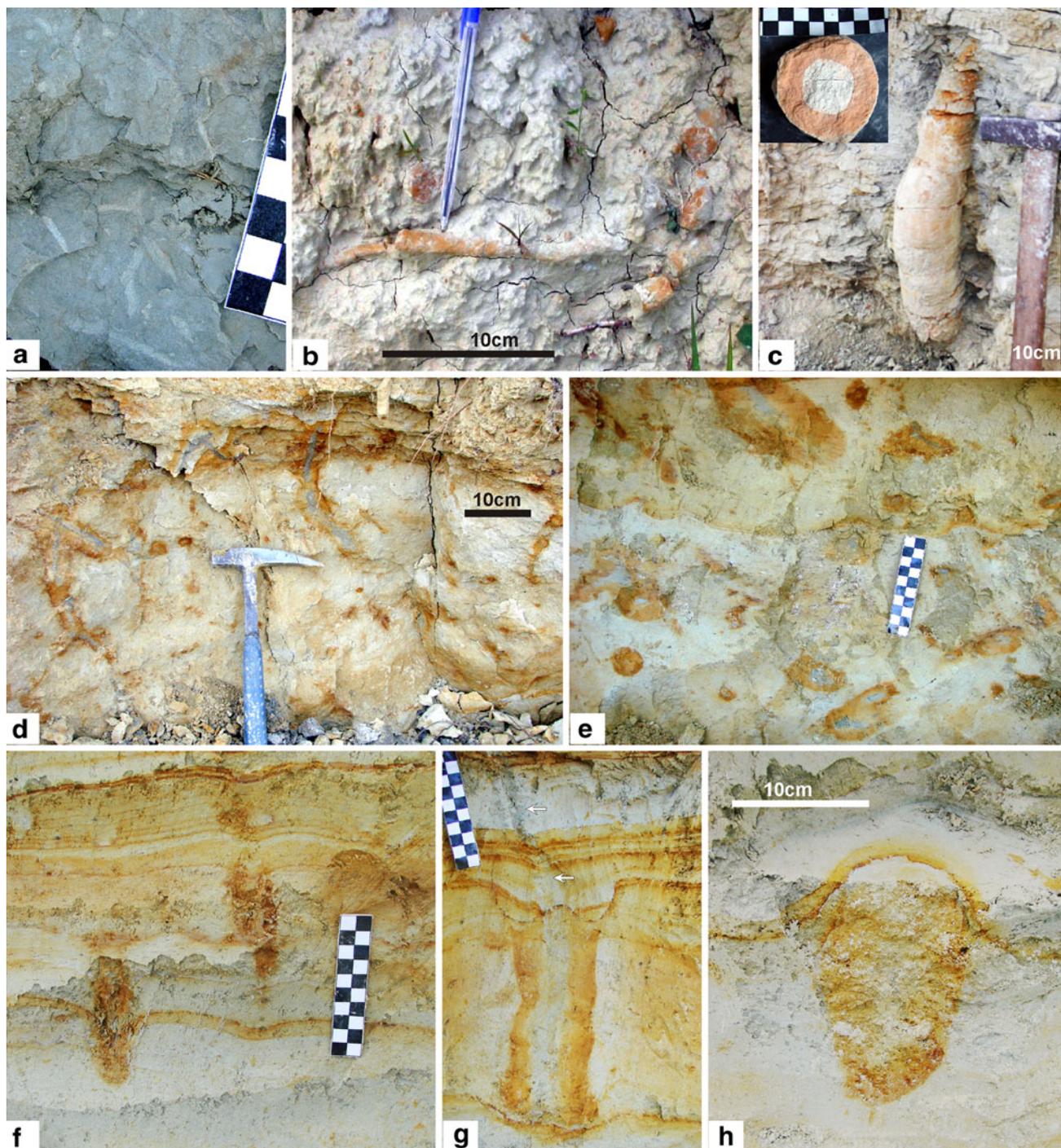


Fig. 7 Trace fossils. **a** thalassinidean Y-branched burrows without walls (type 1) in a clayey *Congeria subglobosa* Beds (Facies association 6). **b**, **c**, **d** and **e** Branched thalassinidean ichnofossils (type 2); **b** Horizontal cylindrical tunnels (FA7); **c** Segmented vertical shaft on outcrop and in perpendicular cross section (FA7); **d** Y-shaped

branches of burrows (FA8B); **e** Horizontal cylindrical tunnels (FA8B). **f**, **g** Simple vertical burrows (*arrows* show escaping trace of buried trace maker) (FA8C). **h** *Conichnus*-like ichnofossil (FA8C). A black field on the scale corresponds to 1 cm

recognized taxa of these genera are endemic to Lake Pannon. A few valves of freshwater *Candona* sp. 1, *C.* sp. 2, *?Candonopsis*, *Cyclocypris* sp., *Darwinula stevensoni*,

Ilyocypris sp. associate with the brackish ostracods and they occur mainly in the FA1 indicating transportation from marginal facies.

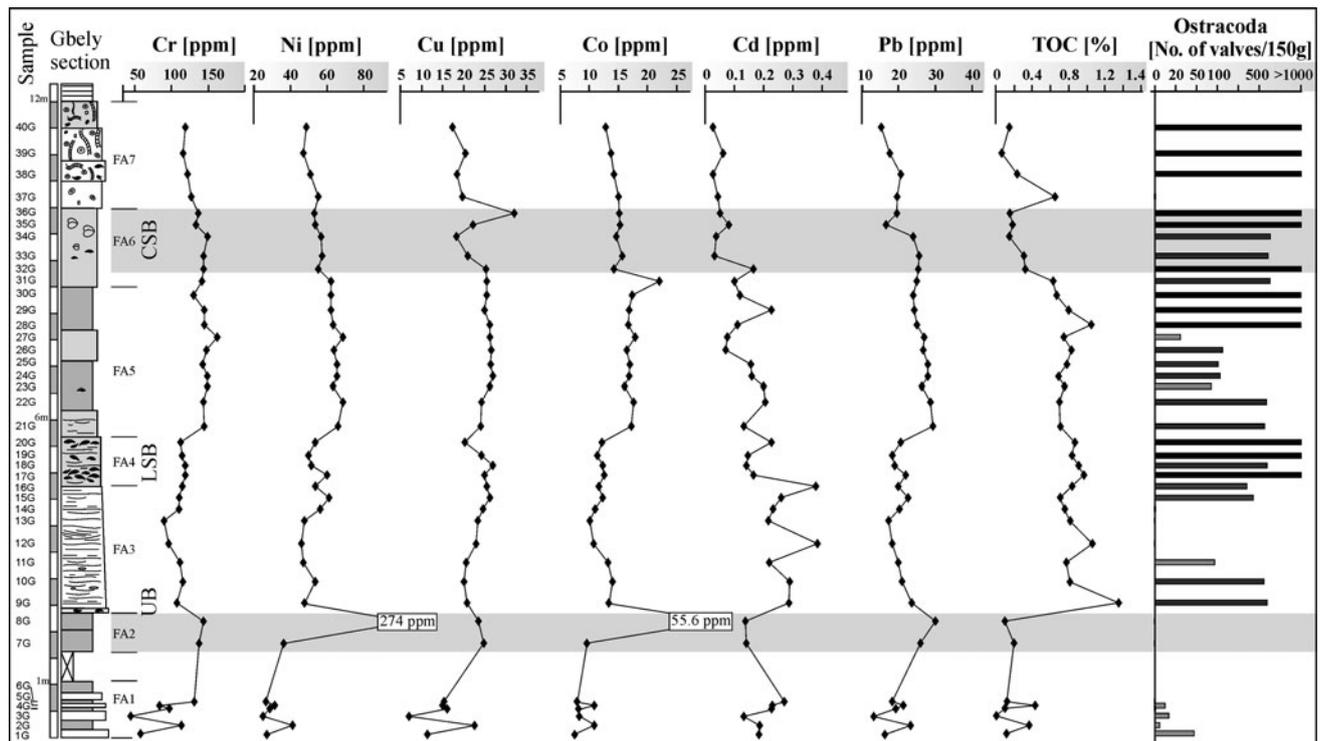


Fig. 8 Concentration of trace metals, total organic content (TOC) and ostracod abundance in sequence with prevalence of clayey sedimentation. For explanation see Fig. 2

Mollusca

Molluscs are restricted to particular beds in the lower part of the sequence (Figs. 2, 3). Disarticulated shells and fragments of *Unio* sp. (bivalve) and *Melanopsis* sp. (gastropod) are concentrated within a thin, brown to violet sandy bed (2.4–2.5 m). These littoral taxa were transported to the FA3. *Limnocardium schedelianum* was recognized in grey clayey silt (4.8–5.7 m) within FA4 (*Limnocardium schedelianum* Beds—LSB). The concentrated open shells were found in concave and convex position, articulated and disarticulated and can be divided into two sub-horizons, according to the abundance of the valves. *L. schedelianum* is common in sublittoral facies (Magyar et al. 2007). The big closed shells of *Congeria subglobosa* occur throughout the 1.5-m-thick clay and silty clay bed (8.5–10.0 m, FA6).

Ichnofossils

Several types of ichnofossils, similar to marine-type trace fossils, have been identified in the sedimentary record of Lake Pannon (e.g. Babinszki et al. 2003; Magyar et al. 2006; Cziczter et al. 2009). The following trace fossils, kept only in an open nomenclature, are recognized at Gbely:

Thalassinidean (type 1) Y-branched burrows without walls (Fig. 7a). They are about 0.4 cm thick in diameter; the filling of the burrows is lighter and slightly contrasts with the surrounding silty sediment. These burrows occur in a clayey CSB (FA6).

Thalassinidean (type 2) burrows with horizontal or slightly inclined cylindrical tunnels (Fig. 7b, e) and vertical, occasionally curved shafts with tube diameter from 0.3 to 6.0 cm and with a maximal vertical extension up to 60 cm (Fig. 7c). The burrow wall is smooth and both, T- and also Y-shaped branches of burrows are observed (Fig. 7d). The filling of the burrows contrasts with the surrounding sediment and it comes directly from the layer covering the burrows (Fig. 7d). The occurrence of these traces shows two maxima in silty and sandy sequences of FA7 and FA8B. Vertical, cylindrical, rarely oblique burrows (shafts), simple in shape with discernible wall (Fig. 7f, g). Less consolidated sediment does not allow a description of ornaments on the burrow wall. The diameter of burrows varies from 2 to 5 cm and their vertical extension reaches 15 cm. These structures occur mainly in silt and sand (FA8C), where they co-occur with thalassinidean (type 2) branching burrows. The conical collapse structures are often coupled with them (see “[Soft-sediment deformation structures](#)”).

Conichnus-like conical ichnofossils, about 5 cm in diameter with a vertical extension up to 12 cm scarcely occur in silt and fine sand of the FA8C (Fig. 7h).

TE, TOC and ostracod abundance

All TE and TOC data are plotted within a lithological log reflecting lithology, sedimentary structures and beds with malacofauna (Fig. 8). Generally, the Cd concentration shows a decreasing trend toward the top of the sequence, which does not correspond to other measured elements.

The measured concentrations in the basal FA1 reflect a clear dependence on the lithology with their lower content in sand and higher content in clay. Cr (43.52 ppm), Ni (25.0 ppm), Cu (6.93 ppm), Co (7.53 ppm), Pb (13 ppm), TOC (below detection limit <0.1 ppm) attain their minimal concentrations in this facies association. Quantitative micropalaeontological analysis indicates that the number of the preserved ostracod individuals is low, varying from 0 to 47. Significant enrichment in Ni (274 ppm), Co (55.6 ppm), Pb (30 ppm) compared to clay of the FA1 were measured in non-calcareous greyish blue homogenous clay (FA2) barren of fossils.

Above the *Unio* Bed, an increase in TOC content (0.71–1.35%) is identified in FA3 and FA4 with horizontal lamination and cross-stratification in the middle part of the body. Slight increase in Cr (109–144 ppm), Ni (50–66 ppm), Cu (20–27 ppm), and Pb (17–29 ppm) content is registered in LSB and it follows the TOC curve. An increase in ostracod abundance just above the *Unio* Bed is followed by their vanishing in the upper part of FA3. The first peak in ostracod abundance with maximum 11,000 preserved individuals (per 150 g of dried sediment) in sample 20G is detected in FA4 indicating a recolonization of the environment.

The overlain homogeneous FA5 rarely contains *Limnocardium* fragments. The number of the preserved ostracod valves varies from 60 to 1,300 individuals (per 150 g of dried sediment). An increased in concentration of Cr (129–161 ppm), Ni (62–69 ppm), Co (16–18 ppm), and Pb (24–29 ppm) is observed. TOC (0.67–1.05%) and Cu (24–27 ppm) content is still high and identical to LSB.

The concentration of Ni (53–62 ppm), Co (14–22 ppm), Cu (18–32 ppm) and TOC (0.15–0.63%) decreases in brown-grey clay of the CSB. Ostracod abundance reaches its second peak, but the number of the preserved valves does not exceed 2000 (per 150 g of dried sediment).

The trend towards high ostracod abundance and decrease of TE and TOC concentration (TOC 0.1–0.65%, Ni 47–55 ppm, Co 13–15 ppm, Cr 115–126 ppm, Cu 17–20 ppm) continues in superimposed heavy bioturbated

silt and fine sand with well-developed thalassinidean burrows (10.0–12.0 m).

Palaeoenvironmental interpretation

The Gbely sequence was deposited in a brackish-water environment influenced by freshwater input and was inhabited by a brackish ostracod association. A generally decreasing trend in concentration of Cd can reflect a decreasing salinity (Waeles et al. 2005). Absence of wave reworked deposition and frequent presence of poorly sorted muddy sand and silt (cf. Van Straaten 1959) as well as a sublittoral mollusc fauna (Magyar et al. 2007; Harzhauser and Mandic 2004) indicated a setting below the fair-weather wave base.

The hydrodynamic energy of Lake Pannon (wave and tide) probably played a minor role in the determination of the morphology and internal stratigraphy of deltas. The greatest lacustrine-deltaic system at the margin of the Vienna Basin was mainly influenced by sediment input (Kováč and Baráth 1995) and fluvial dominated processes formed a “finger-like” delta. The Gbely section reflects part of a lacustrine-deltaic environment, where laterally migrating distributary areas of subaqueous delta formed fingerlike protrusions of sand bars (Jiříček 1990, 2002), separated by mud-rich bays. The deeper lacustrine environment of the embayments was dominated by a quiet clayey and fine silty deposition from suspension (FA2, FA4–FA6).

We interpret the thick upward-fining sandy and silty layer (FA3) as well as pinching sandy bed in FA8A as tempestites—sediments carried by storm-generated flows and deposited below or near storm wave base (e.g. Einsele and Seilacher 1982; Brenchley 1985; Myrow and Southard 1996), which may have carried the freshwater ostracods and littoral mollusks into the basinal part. The interpretation of the other isolated sandy beds is ambiguous for the absence of their sedimentary structures (intercalations of the thin sandy layer of FA1) or for their heavy bioturbation which destroyed the primary sedimentary structures and interfaces (FA7). These two horizons may reflect storm deposits but also may represent coarser sedimentary inputs of turbid underflows discharged directly from fluvial or deltaic distributaries during large floods.

The lacustrine facies associations of a bay passed vertically into a rhythmic deposition of silty clay, silt and fine sand reflecting successive progradation of a prodelta (FA8A–B) and laterally migrating distal bars (FA8C). A prodelta setting with relatively rapid, heterolithic deposition generated the soft deformation structures (FA8A). The small upwarping cusps or siphons were probably formed as a result of spontaneous dewatering of sediments, deposited at quick rates. The medium to large-scale deformation structures restricted to certain, rather narrow zones, vertically

separated and surrounded by non-deformed laminated sets, were formed shortly after deposition and we suggest that they were triggered by overloading, or possible seismic activity (e.g. Sims 1973; Owen 1987; Moretti and Sabato 2007).

Muddy bay, prodelta and distal parts of the delta front environment were extremely favourable for a dense benthic population (cf. Reineck and Singh 1980). An ichnofauna appeared together with benthic ostracods, abundant in both taxa and specimens, in the CSB and superincumbent beds. This appearance of meiofauna is associated with low TOC concentration reflecting a decrease in input or higher consumption of organic matter. The geochemical and palaeontological record supposes a fully oxygenated environment also underlined by white and transparent ostracod valves. Interestingly, blue-grey and brown clay (FA5) have identical TE concentrations and ostracod species association, but no macro- and ichnofauna has been observed. The pyritized ostracod carapaces occurred only in this FA, which indicates reducing conditions below the surface (Oertli 1971). An anoxic event (FA2) detected by a high concentration of Ni, Co and Pb and a noticeable absence of fossils and bioturbation occurred only as a local phenomenon (see “Discussion”).

The silty and sandy prodeltaic to distal delta front environments above the CSB offered almost ideal conditions for settlement of ichnofauna. The trace fossils found in the Gbely section are largely attributed to thalassinidean burrows mostly interpreted as combined feeding and dwelling burrows related to crustaceans (e.g. Frey et al. 1984; Bromley 1996; Bishop and Williams 2005). These ichnofossils may represent species that tolerated brackish conditions or also may reflect evolution of lowered salinity tolerances for the constructors (e.g. Magyar et al. 2006; Wesselingh et al. 2006). Heavy bioturbation as well as the presence of large-diameter thalassinidean burrows means a relatively well-oxygenated bottom (cf. Savrda and Bottjer 1986; Bromley and Ekdale 1984). The changes in velocity of sediment inflow perturbed colonization in FA8A and provided narrow colonization windows associated with high deposition rates and coupled with conical sedimentary structures in FA8C (Fig. 5a).

Discussion

The CSB established in the oxygen-depleted hypolimnion of a stratified lake (Harzhauser and Mandic 2004). This implies a lack or depletion of meiofauna (Bodergat et al. 2002; Ruiz et al. 2006) because only a few ostracod species can adapt to such conditions (Ruiz et al. 2005).

A horizontal variability in saturated dissolved oxygen concentration is low in the modern lakes (besides littoral) and if it is high it depends on the parameters as littoral

photosynthetic production, size and depth of the lake, or type of thermal stratification (Wetzel 2001, p. 161). At that point, we also encounter the problem of renewal of deep-water and mixing of river and brackish waters in a hydrologically open lake under warm and humid climate where the salinity gradient is small (for salinity data see Kováč et al. 1998; Harzhauser et al. 2007). The sediment discharge from rivers was high (Vakarcs et al. 1994) and it reached basinal clay (Harzhauser et al. 2008), far away from the supposed shoreline. Thus not only sublittoral, but also a deeper lake environment might have been efficiently supplied with oxygen and nutrients.

The association (Fig. 6) of brackish benthic *Cyprideis obesa*, *Hemicytheria folliculosa*, *H. reniformis*, *Amplocypris abscissa*, *A. recta*, *Loxoconcha granifera*, *Cypria abbreviata* and paratethyan Candoninae is widespread in the Vienna Basin and a number of ostracod species in the association increases toward the south and open lake facies. If we consider ostracod species abundance at the outcrop Gbely, it increases from LSB to CSB and the number of preserved ostracod valves reaches maximal values in the both beds; TOC and TE concentrations in the CSB are lower or comparable to the LSB signalling the similar oxic conditions.

The benthic ostracods can penetrate into the sediment down to a depth of 6 cm and can effectively bioturbate the sediment (Danielopol et al. 1988), but only if the redox potential is higher than +200 mV (Yin and Geiger 1995). They seldom occur in anaerobic sediment; avoid it and they move into oxygenated habitats (Danielopol et al. 1990; Yin and Geiger 1995).

Physicochemical and microbial properties in the burrow of *Biffarius arenosus* (living thalassinidean shrimp) can reflect more of the surface sediment conditions than the surrounding subsurface ones. Thus, the light yellow/brown colour of the burrow walls can reflect a primary colouration caused by oxidising conditions in the burrow (Bird et al. 2000) articulated at Gbely section by postsedimentary pigmentation from ground water. A redox potential (+213 and +243 mV) in the burrow of *Biffarius arenosus* (Bird et al. 2000) is in a good agreement with minimal values for an occurrence of the ostracods. We consider that the redox surface and subsurface conditions were higher than +200 mV [limit level indicating a reduction of Fe^{3+} to Fe^{2+} (Lellák and Kubíček 1991)] in the FA7 and FA8C and oxic conditions prevailed also at this part of the studied outcrop.

The reducing redox conditions can exist in the subsurface sediments, as in the case of *Biffarius arenosus* (Bird et al. 2000), but in the case of the FA7 and FA8C, it is important to pay an attention to the fact that no pyrite or limonitic concretions were found inside the ostracod valves (see Oertli 1971).

Thus, the fluvial-dominated lacustrine-deltaic system in the Vienna Basin carried a sufficient amount of nutrients and oxygen to the lake and induced a proliferation of the eutrophic green algae and meiofauna in the littoral (Pipík et al. 2004; Harzhauser and Tempfer 2004) and sublittoral (Cziczter et al. 2009; Harzhauser et al. 2008), which benefit from a high nutrient input (Bodergat et al. 2002).

The Gbely section demonstrates local oxygen depletion (FA2) perturbed benthic life in the Lake Pannon sublittoral. Since the FA2 is situated between two horizons of isolated sandy/silty beds (FA1, FA3) interpreted as tempestites or flood-generated underflows deposits, we assume that these events could locally change the bottom topography within a complex lacustrine-deltaic environment where open deeper embayments with offshore mud, which separated individual distributional units, had a primarily fully oxygenated regime (good connection to the lake circulation). In consequence of sudden coarser sedimentary inputs of under-water flows discharged during large floods or storm return-flow deposits (tempestites), a temporal semi-isolation of these embayments might have occurred. Worsened ventilation could have led to oxygen depletion and occurrence of a local anoxia, which was wiped out by subsequent larger storm activity. Flood-generated hyperpycnal flows or storm currents emplaced not only detritic material and nutrients but also oxygen to the lake bottom and re-established life. *Caspiocypris fahrioni* occurred only in that renewed environment together with *Cyprideis obesa*. *Caspiocypris fahrioni* colonized the environment immediately after the anoxic event, but it lacks in diversified ostracod associations of the FA5 to FA8. Because *C. fahrioni* occurred after the stress conditions, we suppose it is a pioneer species. The same could be true for *Cyprideis* (Gamenick et al. 1996), but both recognized species of this genus occurred in a diversified association in the Vienna Basin.

Conclusions

The brackish lacustrine-deltaic sequence deposited below the fair-weather wave base evolved from a deeper clayey and silty environment of protected bay to silty/sandy prodelta and distal bars environment with high sedimentary input. Local bottom changes in the sublittoral environment influenced bottom circulation and saturation of the water with oxygen. An expansion of a local anoxic event conditioned bottom colonization. Storm activity and flood-generated underflows wiped out these conditions and a normal oxic environment was recovered by meiofauna when the stress factors terminated. A muddy environment of a bay, including the *Congeria subglobosa* Beds, was the most favourable for the development of the benthic ostracod community, while silty and sandy prodelta to distal bar

environments were favourable to a thalassinidean ichnofauna.

The changes in rates of sediment inflow were a main limiting factor of bottom life during prodelta and distal delta front deposition. A period of rapid deposition buried colonization and generated non-bioturbated beds with well-preserved primary sedimentary structures as well as soft-sediment deformation structures.

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