ABSTRACT
The study of eight stratigraphic sections at the margin of the semi-enclosed Zsámbék Basin (Hungary) allows the sedimentary anatomy of oolitic–bioclastic systems in the Sarmatian of the Central Paratethys to be reconstructed. The mollusc, foraminiferal and ostracod associations indicate that the carbonate systems are Latest Badenian to Late Sarmatian in age. The Lower–Upper Sarmatian deposits are organized in superimposed subaqueous dunes prograding towards the basin on a low-angle ramp. During the Late Sarmatian, the ramp underwent subaerial erosion linked to a moderate relative fall in sea-level. Lagoonal deposits were later formed and microbial–nubeculariid–bryozoan–serpulid buildups were emplaced. The ‘abnormal’ marine conditions of the Sarmatian, conducive to the development of a poorly diversified flora and fauna and dominant non-skeletal grains, are linked to fluctuating salinities, mesotrophic to eutrophic conditions and perhaps high alkalinity.

Keywords Buildups, carbonates, Hungary, Miocene, oolites, Paratethys.

INTRODUCTION
Around the Eocene/Oligocene transition, the ancient Tethys Ocean had vanished and was replaced in its western part by two relict seas, the Mediterranean and the Paratethys (Rögl & Steininger, 1983; Rögl, 1998a, 1999). The Paratethys was an enclosed sea that suffered repeated isolation episodes, with narrow seaways connecting it not only to the Mediterranean but also to the Indo-Pacific and even to the Boreal Ocean (Rögl & Steininger, 1983; Rögl, 1998a,b, 1999; Steininger & Wessely, 2000; Meulenkamp & Sissingh, 2003; Popov et al., 2006).

During the Miocene, the Central Paratethys developed within and around the Carpathians where thick marine to continental deposits accumulated, particularly in its central and largest part, the Pannonian Basin (Fig. 1). The Pannonian Basin comprises several sub-basins between emerged lands; among them is the Zsámbék Basin west of Budapest (Fig. 2).

Because of episodic isolation from the Mediterranean, the chronostratigraphy of the Paratethys is based on regional stages, with the generally accepted correlations between the two systems as follows: Badenian = Langhian to Early Serravallian; Sarmatian = Late Serravallian;
and Pannonian = Tortonian + Messinian (Rögl, 1998b). Most of the Badenian deposits are interpreted as fully marine, while the Sarmatian deposits have traditionally been considered as brackish, transitional towards the freshwater environments of the Pannonian (Papp, 1956; Papp et al., 1974).

Numerous papers have been devoted to the Sarmatian, but they mainly deal with the palaeontological and stratigraphic aspects, a notable exception being that by Krézsek & Filipescu (2005) on the Transylvanian Basin where some sedimentological studies were conducted. The Sarmatian deposits of Austria, however, were studied intensively and numerous papers have documented their lithology, stratigraphy, palaeontology, palaeoecology and, more recently, geochemistry (Friebe, 1994; Harzhauser & Kowalke, 2002; Kosi et al., 2003; Harzhauser & Piller, 2004a,b, 2007; Kováč et al., 2004; Latal et al., 2004; Piller & Harzhauser, 2005; Gross et al., 2007b; Harzhauser et al., 2007; Piller et al., 2007; Schütz et al., 2007).

In Hungary, much attention has been dedicated to the palaeontological content (including the biostratigraphy) but sedimentological information is relatively rare. Moreover, many of the papers dealing with the Sarmatian are written in Hungarian (some of them unpublished in theses or preliminary reports) and thus are not easily accessible.

The best-exposed Sarmatian deposits of the Pannonian Basin are located in the region around Budapest, especially near Zsámbék (Boda, 1974a) (Fig. 2). A number of key outcrops/sections were visited in this basin and their study allows, for the first time, a general reconstruction of the sedimentary organization. Information from the literature and a comparison with data from several boreholes drilled in the same region will also improve the understanding of the sedimentary dynamics and palaeoceanography of the Central Paratethys.

**GEOLOGICAL AND STRATIGRAPHICAL SETTING**

The Zsámbék Basin is located 30 km west of Budapest (Fig. 2). It is a Middle Miocene
semi-enclosed basin, 30 km long and 20 km wide, which opened to the west. The Miocene sequences comprise Badenian to Pannonian deposits (Jámbor, 1967, 1969). The Sarmatian carbonates crop out along a 2 to 5 km wide belt fringing the emerged lands or on shoals (Fig. 2). In the basin, underlyng the Pannonian lacustrine deposits, boreholes (Perbál, Mány and Budajenő) revealed 80 to 180 m of marl-dominated sequences, with some carbonate and evaporite interbeds in Budajenő (Jámbor, 1974; Görög, 1992).

The precise age of the Sarmatian limestones is uncertain. The biostratigraphy of the Sarmatian marl-dominated deposits of the Zsámbék Basin was established by Görög (1992) who distinguished three foraminiferal zones: the Elphidium reginum and the Elphidium hauerinum zones (Early Sarmatian) and the Spirolina austriaca zone (Late Sarmatian). This zonation correlates well with other bio(eco)stratigraphic subdivisions that have been used in Hungary and more generally in the Paratethys (Görög, 1992). These subdivisions are based on nannoplankton (Nagymarosy, 1982; Schütz et al., 2007), diatoms (Hajós, 1976, 1986), molluscs (Boda, 1971; Kojumdgieva et al., 1989; Harzhauser & Piller, 2004b; Gross et al., 2007b) or ostracods (Zelenka, 1990). Oolitic interbeds are reported from the Early Sarmatian (Kozárd Formation) of this region (unpublished borehole logbooks, Hungarian Geological Institute, Budapest) but the massive carbonate deposits of the margins classically are attributed to the Late Sarmatian Tinnye Formation (Boda, 1954, 1974c; Jámbor, 1971; Fodor et al., 2000).

MATERIAL AND METHODS

Research in the field was carried out on eight stratigraphic sections situated in six localities. These sections, exposed mostly in quarries, were measured and photographs taken. Seventy-eight sediment samples were collected from the outcrops for petrographical and palaeontological analyses. Additional observations and sampling were made on two small outcrops near Budapest (Diósd and Rákos).

In the laboratory, loose sediment samples were soaked in water-diluted hydrogen peroxide (about 30%) to facilitate disaggregation and were then wet-sieved through strainers with meshes of five different sizes: 2, 1, 0.5, 0.25 and 0.125 mm. The residues were dried and studied with the aid of a stereomicroscope to identify the genera or species present and estimate the number of individuals or fragments. Polished slabs and thin sections of indurated rock samples were prepared to document the lithological, biogenic and petrographic characteristics of the limestones. Correlations were later made between outcrops, and between outcrops and boreholes, on the basis of sedimentological and palaeontological characteristics.

DESCRIPTION OF THE SECTIONS

From north to south, eight stratigraphic sections were studied. These include sections at Tinnye, Zsámbék, Páty, Biatorbágy, Sóskút and Győró (Fig. 2).

Tinnye village

This section (Fig. 3A) is located near the basement (metamorphic rocks) in the north-eastern part of the village. It comprises about 6 m of fine-grained and argillaceous sandstones with some scattered ooids in coarser-grained deposits. In the sandy beds near the base, the foraminifera (diverse and abundant miliolids, among them well-preserved Borelis sp.) and the great abundance of ostracods (Xestoleberis sp.) point towards normal saline to even slightly hypersaline conditions (van Morkhoven, 1963), probably in lagoonal settings subjected to siliciclastic inputs. Small-scale hummocky cross-stratifications (Ricci Lucchi, 1995) and ripple marks below sample 1 and accumulations of molluscs (Venerupis, Ervilia, Granulolabium) in sample 2 suggest a protected shoreface setting. The presence of S. austriaca in sample 2 indicates a Late Sarmatian age. Sample 3 contains an assemblage suggesting slightly brackish conditions: foraminifera (predominantly Ammonia beccarii and Elphidium macellum), ostracods (Aurila notata and Hemicytheria omphalodes) and some charophyte oogonia (van Morkhoven, 1963; Cernajsek, 1972; Murray, 1991). At the top (samples 4 and 5) an oolitic limestone with red and green algae, gastropods (mostly Granulolabium) and nubeculariid foraminifera is present.

Tinnye-Perbál

The Sőreg quarry section (Fig. 3B) was considered to be the type locality for the Late Sarmatian (= Bessarabian) Tinnye Formation (Boda,
The foraminifera and molluscs of this quarry were described briefly by Meznerics (1930). The sedimentary succession of this small abandoned quarry consists of two units, from bottom to top as follows:

- **Unit A** is formed of an oolitic grainstone, 2 m thick, with large-scale cross-bedding (Ricci Lucchi, 1995) and cross-trough stratification. Non-skeletal grains are mainly concentric ooids, associated with some mixed concentric–radial ooids. The grainstone also contains some oncoids, micritic aggregates and oolitic lithoclasts. Skeletal grains are benthonic foraminifera (dominant miliolids), bivalves (Obsoletiforma, Venerupis) and gastropods (abundant Potamides). This facies is interpreted as deposited in an inner ramp ooid bar setting. Unit A is truncated by an erosional surface.

- **Unit B** begins with a 0.3 m thick laminated clayey layer intercalated with thin oolitic beds. Above this layer are 2 m of oolitic limestones. The silty layer contains well-preserved benthonic foraminifera, gastropods (such as Granulolabium bicinctum), bivalves and ostracods. Poorly diversified, the foraminifera are represented by dominant (90%) A. beccarii, Elphidium macellum and Elphidium obtusum. The ostracods are relatively diverse (eight species), with numerous Cyprideis pokorny and Euxinocythere sp. among them; they characterize the Hemicytheridea hungarica–Leptocythere cejicensis Assemblage zone of the uppermost Sarmatian (Zelenka, 1990). The faunal associations suggest a warm-water brackish environment (van Morkhoven, 1963; Puri et al., 1969; Murray, 1991). The intercalated thin carbonate beds are oolitic packstones containing micritic fragments and nubeculariids. Micritic fragments or benthonic foraminifera form the nucleus in many ooids. The skeletal grains are mainly benthonic foraminifera (miliolids), gastropods and some bryozoans in a peloidal matrix. The faunal content and the sedimentological features of the silty bed are typical of deposition in a relatively warm-water, normal or even hypersaline lagoonal environment (Haig, 1988). The overlying oolitic grainstones to packstones contain an assemblage of peloids, rare proto-ooids, benthonic foraminifera (miliolids) and abundant molluscs (notably Obsoletiforma, Sarmatimactra, Venerupis, Solen and Granulolabium) which also indicates a lagoonal setting (Koutsoubas et al., 2000).

**Zsámbék**

This abandoned quarry, 8 m high, displays two sedimentary units separated by a well-defined planar surface (Fig. 4): 

- **Unit A** consists of oolitic grainstones organized in east/south-eastward prograding beds. The grainstones contain peloids, rare aggregates and proto-ooids, benthonic foraminifera, molluscs (rare Venerupis, Modiolus, Mytilaster, Gibbula and Potamides) and red algae, corresponding to an inner bar depositional environment.

- **Unit B** consists of 6 m of bioclastic–oolitic limestones containing proto-ooids, abundant...
peloids, ostracods, benthonic foraminifera (among them *S. austriaca*, nubeculariids, dominant miliolids and *E. macellum*) and fragments of serpulids, bryozoans and molluscs. The occurrence of *S. austriaca* indicates a Late Sarmatian age. Among the ostracods, very frequent *Xestoleberis* spp., together with the foraminiferal fauna, suggests marine to hypersaline conditions (van Morkhoven, 1963). The bivalves are represented by numerous infaunal elements (*Plicatiforma, Inaequicostata, Obsoletiforma, Ervilia, Venerupis, Tapes*, etc.) and rare, bysally attached epizoans (*Modiolus* and *Musculus*). Most of the gastropods are marine herbivores (*Gibbula, Hydrobia, Potamides* and *Granulolabium*) but some are carnivores (*Acteocina*) or scavengers (*Duplicata*) and a number of freshwater forms also occur (*Valvata, Gyraulus*). Carbonate buildups occur within the grainstones as small lens-like microbial, red algal and serpulid bodies, decimetre to metre long and decimetre high; they are sometimes associated with encrusting bryozoans belonging to three species (*Cryptosula pallasiana, Conopeum reticulum* and *Tubulipora* sp.). Unit B is interpreted as deposited in a lagoonal environment with possible salinity changes and subaerial exposure (calcrete and stalactitic cements: Fig. 5A and B).

**Páty**

This quarry (Mézes Hill quarry) reveals a section about 150 m in width and 40 m in vertical thickness (Fig. 6). The lithofacies is composed largely of graded bioclastic grainstones to rudstones with abundant mollusc shells and red algae, but lesser amounts of oolites. At the top, the facies is more micritic and contains nubeculariid foraminifera.

Twelve south-west prograding units were identified; they correspond to large-scale subaqueous dunes 3 to 5 m in thickness and at least several tens of metres in width, limited by reactivation surfaces. The internal beds of the dunes are south-westward dipping (5° to 15°), indicating a general basinward progradation. The microfacies analysis of the dominant grainstones revealed concentric proto-ooids, peloids, some aggregates, gastropods, bivalves and benthonic foraminifera (miliolids) (Fig. 7A and B). Detrital grains (quartz, micas and quartzite) are always present, dispersed in the sediment. The morphology and composition of the dunes indicate an inner ramp depositional environment. Several hemispherical bioherms, about 50 cm thick and 1 m wide, are observable on the quarry wall (Fig. 6); they consist almost exclusively of encrusting bryozoan colonies (*Schizoporella unicornis*) with minor quantities of serpulid tubes.
This natural section (Kőgomba section) is about 25 m thick (Fig. 8). From bottom to top, it displays:

- Sandy limestones with a rich fauna of foraminifera, gastropods, bivalves (among them pectinids like Crassodoma multistriata indicating a Badenian age) and echinoids (Strausz, 1923; Csepreghy-Meznerics, 1960). The most abundant constituents identified in thin sections are micritized fragments, bivalves, red algae, diverse benthonic foraminifera, bryozoans and some ooids (concentric ooids and proto-ooids), indicating a shoreface setting.

- The contact between the Badenian and the Sarmatian is unclear because it occurs on the grass slope (Fodor et al., 2000). The Sarmatian deposits are represented by about 10 m of bioclastic–oolitic limestones with some gravels and common coquina beds. Metre-high and decametre-long, south-westward dipping, low-angle subaqueous dunes were observed in these sediments, indicating a basinward progradation. The bioclastic–oolitic limestones are grainstones to packstones with variable amounts of concentric ooids, micritized ooids, proto-ooids, peloids, benthonic foraminifera and mollusc fragments. Detrital grains, such as quartz and feldspars, are always present in minor quantities. Near the top of the section, two ‘pebbly’ layers were identified. The lower layer contains centimetre-size to decimetre-size large nodules composed of serpulids, coralline algae and nubeculariids. The upper layer is a conglomeratic bed with basement-derived fragments indicating a sequence boundary which separates an underlying Unit A and an

Fig. 5. (A) Calcrete structure delineated by iron concentrations (Unit B, Zsámbék). (B) Dissolution cavities in nubeculariid-microbialite boundstones. The cavities are partly filled with: ‘1’ transparent calcite rimming the cavity walls; ‘2’ iron-rich coating; ‘3’ stalactitic calcite; ‘4’ iron-rich coating (Unit B, Zsámbék).

Fig. 6. Páty quarry section. Upper part: sketch of the western part of the Páty quarry showing six superimposed subaqueous dunes and a bryozoan buildup; lower part: field view of a bryozoan buildup (hammer for scale is approximately 0.3 m long).
overlying Unit B (Fig. 9). The conglomeratic bed is composed of reworked oolitic blocks, centimetre to decimetre in diameter, and of isolated smaller dark quartzite pebbles. The oolitic blocks are encrusted by red algae (dominant), serpulids, nubeculariids and microbialites. These coatings are a few centimetres thick and occur on all surfaces of the blocks indicating that they were episodically overturned (Fig. 10). Units A and B were deposited in an inner ramp or platform setting, sometimes in lagoons. No index fossil was found in these deposits.

Sóskút

Sóskút is the most representative carbonate platform in the studied basin and is exposed along the banks of the Benta river. On the western flank, the Sóskút quarry (ancient Roman quarry) is about 250 m long and 20 m high (Fig. 11). The outcrop can be subdivided into two units separated by a major erosional surface identified across the whole Sóskút area:

- Unit A can be subdivided into five sedimentary sub-units. The older sub-units are composed of grainstones and packstones with abundant peloids, part of them being identified as micritized concentric ooids, benthonic foraminifera (*Elphidium*, *miliolids*), bivalves (*Venerupis, Modiolus* and *Sarmatimactra*), gastropods (*Potamides, Gibbula* and *Clavatula*) and serpulids (Fig. 12A). Among the gastropods, abundant and well-preserved *Mohrensternia* suggest an Early Sarmatian age. The younger sub-units are composed of grainstones with concentric oolites, oolitic lithoclasts, protocoides, bivalves and benthonic foraminifera (*miliolids*) (Fig. 12B). Detrital grains (mostly quartzite) are rare but always present. The sub-units correspond to subaqueous dunes, several tens to hundreds of metres long, separated by local reactivation surfaces, sometimes delineated by greenish, sandy argillaceous beds. Sub-unit 1 is a 20 m high dune with tabular foresets dipping 20° towards the west. Sub-units 2 to 5 are metre-thick and their foresets dip 5° to 10° towards the south. Unit A thus is constituted of inner ramp material transported basinward in an outer ramp setting.

- Unit B rests on the different sub-units of Unit A (no. 5 to the east and no.1 to the west; Fig. 11). Unit B is composed of some 5 m of oolitic limestones with clinoforms prograding west/northward. The oolitic limestones are grainstones with peloids, micritized oolites, oncoidal lithoclasts, benthonic foraminifera (*miliolids*) and fragments of bivalve shells (Fig. 12C). Unit B also displays a number of small cauliflower-like or columnar buildups made of abundant serpulid tubes and encrusting bryozoan colonies (mostly *S. unicornis*). The buildups are associated with gastropod-rich wackestone beds. Unit B is inter-
interpreted as deposited in a lagoonal setting under high-energy conditions and basinward transport of material.

The erosional surface is characterized by a continuous pebbly deposit that truncates Unit A. This horizon contains early-cemented limestone blocks of Unit A, from a centimetre to up to a metre across, embedded in the oolitic limestones of Unit B (Fig. 11). The blocks generally are coated with composite crusts composed mainly of nubeculariids associated with red algae, serpulids and peloidal microbialite. This surface clearly is erosional as it transects several sub-units of Unit A, sometimes forming palaeo-cliffs several metres high. Direct evidence for subaerial erosion is not observed in the Sóskút quarry, but early lithification of the deposits of Unit A is documented by blocks of various sizes embedded in Unit B, suggesting that subaerial erosion occurred after the deposition of Unit A. Moreover,
the deposits of Unit B often display stalactiform calcitic cements indicating meteoric vadose cementation (Fig. 5B).

On the eastern Calvary Hill above the village of Sóskút a 35 m thick natural section was first studied by Fodor et al. (2000) and is re-investigated in this study. It shows bioclastic and oolitic limestones with some gravel beds (Fig. 13). Fodor et al. (2000) interpreted the depositional environments as back-barrier lagoons to submarine slopes with south-westward to southward transport directions. The succession is composed of six lithostratigraphic sub-units. Sub-unit 2 shows dome-shaped, decametre-long structures. The top of these structures is obscured by a level erosional surface and younger beds often onlap the bedding planes of older beds. Such dome-shaped structures are typical of spillover lobes (Ball, 1967), here transected perpendicularly to the south-westward transport direction. Other sub-units are subaqueous dunes (e.g. sub-unit 3) or sub-horizontal deposits (e.g. within sub-units 1, 4, 6). In the uppermost part of the section, subaqueous channels and isolated dunes occur (sub-unit 5). Petrographic investigations in sub-units 2 and 3 reveal a rather similar carbonate composition; they consist of grainstone with diverse amounts of peloids, micritized concentric ooids, micritic and oolitic lithoclasts, aggregates, rare proto-oncocoids and radial ooids, bivalves, gastropods, ostracods, benthonic foraminifera (dominated by miliolids and elphidiids), some bryozoans, serpulids and, at the top, nubecular-
grains is noticeable in all samples. In the lower part of the section, sample 6 contains numerous charophyte oogonia, well-preserved gastropod shells, an ostracod fauna with dominant large *Aurila* cf. *merita* and an assemblage of foraminifers (mainly *Elphidium hauerinum*, *E. macellum* and *E. aculeatum*) indicative of the Early Sarmatian. In the uppermost part of the section, the occurrence of *S. austriaca* indicates a Late Sarmatian age. Neither buildups nor major unconformity were observed in this section, thus the different sub-units probably belong to a single lithostratigraphic unit composed of superimposed prograding-aggrading sub-units.

East of Sóskút, near Budapest, two small isolated Sarmatian outcrops were sampled at Rákos (a railway cut) and on a hillside at Diósdc (Fig. 2). Their deposits bear a strong resemblance to the carbonates described above: they are composed of grainstones and packstones and contain micritized concentric ooids, peloids, some aggregates, bryozoans, bivalves and benthonic foraminifers (miliolids, elphidiid and rare nubeculariids).

**Gyúró**

This ancient quarry (Szent György Puszta quarry) was first studied by Kátay (1983). Two units were identified on the outcropping 10 m high wall (Fig. 15). The erosive surface between units is irregular and weakly marked, sometimes even planar.

- Unit A, made of oolitic grainstone and occasional mollusc rudstone, comprises at least four large-scale subaqueous dunes, separated by weakly pronounced erosion and reactivation surfaces. Each dune is about 1 to 4 m thick and 100 m long and progrades to the east/south-east. The molluscs are represented by abundant bivalves (mostly *Obsoletiforma* and *Venerupis*, but also *Inaequicostata*, *Sarmatimactra* and *Musculus*) and rarer gastropods (*Duplicata*, *Gibbula* and *Potamides*). The frequent occurrence of *S. austriaca* (Fig. 16A and B) in the uppermost part of Unit A (second dune) indicates a Late Sarmatian age.

- Unit B, 3 to 4 m thick, is formed mainly of oolitic grainstone and, near the top, contains small hemispherical buildups (Fig. 15); they were described by Kátay (1983) as stromatolites, but are in fact made up principally of numerous stacked bryozoan crusts. The oolitic grainstones represent east/south-eastward prograding local conditions.
Sedimentary organization

In six of the investigated sections the sedimentary organization is rather similar, with two main units separated by an erosional unconformity. Unit A generally comprises basinward prograding subaqueous dunes and the overlying Unit B is composed of lagoonal deposits. These constant features suggest that Units A and B are similar throughout the Zsámék Basin. This suggestion is confirmed by stratigraphic studies: at the base, Unit A has been dated from the Early Sarmatian in the Sósátk quarry and Calvary Hill and at the top from the Late Sarmatian in Gyúró and Calvary Hill. Unit B belongs to the Late Sarmatian S. austriaca zone in Tinnye Village, Tinnye-Perbál and Zsámék quarry. The erosional surface is consequently a regional index surface (within the Late Sarmatian S. austriaca zone) that can be used for correlations. The Sarmatian carbonate deposits thus are composed of two main sequences above the Badenian deposits (Fig. 8): an Early–Late Sarmatian Sequence A (= Unit A) and a Late Sarmatian Sequence B (= Unit B). The main erosional surface between Units A and B belongs to the Late Sarmatian S. austriaca zone.

The distribution of the studied Sarmatian carbonates was mapped by Jámbar (1967) and Fodor et al. (2000). These carbonates surround the Zsámék Basin. To the west and the east they rest on basement rocks, but their initial extension is unknown because of subsequent erosion. To the south, the carbonates constitute a semi-isolated shoal. Observations presented in this paper, together with those of Fodor et al. (2000), have been integrated into a sedimentary model (Fig. 17) which shows that the prevailing directions of transport in Sequence A vary strongly from one place to another in the Zsámék Basin. Large-scale subaqueous dunes, spillovers, subaqueous channels and oblique tabular beds indicate transport of material towards the centre of the basin, approximately perpendicular to the slope directions. Despite the suggestion that tidal currents may have been active in the Central Paratethys during the Sarmatian (Mandic et al., 2008a,b), the action of tides in the investigated area was not recorded clearly: (i) no evidence...
typical of tidal structures was found (argillaceous drappings, reverse flow directions, tidal channels, etc.); and (ii) during the Sarmatian, the Paratethys was almost isolated from the Mediterranean and consequently was far from oceanic influences (Rögl, 1998b). The centripetal organization of sediment transport is thus better coupled with wind and wave action and eventual downslope gravity control.

The size and organization of the metre-scale to decametre-scale sedimentary structures and the composition of the deposits provide information permitting a broad estimate of the palaeobathymetric changes. The depth of formation of subaqueous dunes generally is estimated as four to five times their maximum thickness (see review in Anastas et al., 1997):

- **Sequence A.** In Tinnye the dunes are 1 to 2 m thick; in Páty, Biatorbágy and Gyúró they reach 3 to 5 m; and in Sóskút they are about 10 m high. Consequently, the reconstructed organization of the outcrops is a ramp system with water depths from a few metres in proximal areas to around 40 to 50 m in distal zones. The presence of spillovers and the highest dunes in the Sóskút area is noticeable, further attesting to the presence of a slope deepening at the margin of the ramp. The top of Sequence A is a mostly flat, erosional surface, with locally reworked Sarmatian carbonate blocks and pebble-size basement rocks.

- **Sequence B.** Marine, lagoonal and brackish deposits occur in Tinnye. In Biatorbágy, the sediments are marine lagoonal carbonates with small nubeculariid–bryozoan–microbial buildups and some calcite levels (Figs 4 and 5A), indicating shallow lagoonal settings. Presence of decimetre-thick to metre-thick subaqueous dunes indicates a maximum depth of a few metres. Sequence B is a widely extending, lagoonal carbonate platform capping the underlying ramp system.

From the general sedimentary organization proposed here, Sequence A is interpreted as deposited during a sea-level highstand. The deposits of Sequence B are transgressive, but were deposited mainly during a second highstand, near the boundary with the Pannonian deposits. Between these two sequences a subaerial exposure probably occurred, during which the top of Sequence A was eroded. The sea-level drop associated with the subaerial exposure was of limited amplitude as the erosive event created comparatively low-relief structures of a few metres. A precise estimation of the time gap linked to subaerial erosion is presently impossible. Subaerial exposure occurred during the Late Sarmatian *S. austriaca* zone. This situation is not known from other basins of the Central Paratethys. For instance, in Austria, the main unconformities are located at the base and at the top of the Sarmatian deposits and another one was identified between the Early and the Late Sarmatian (Harzhauser & Piller, 2007). In Austria, the Late Sarmatian carbonate deposits of the *Prosononion granosum* zone lasted about 500 kyr, between 12.1 and 11.6 Ma (Harzhauser & Piller, 2004b). The Late Sarmatian unconformity of the Zsámbék Basin may be related to the minor unconformity that occurred in Austria during the *P. granosum* zone, between the deposits of the upper *Ervilia*
mollusc zone and the Sarmatimactra vitaliana mollusc zone (Harzhauser & Piller, 2004b). However, S. austriaca was found below and above the erosional unconformity, while in Austria this foraminifera occurs only in the uppermost part of the carbonates, far above the unconformity. Consequently, a detailed correlation of the studied sections with those from other basins is hazardous. In any case, the gap evidenced in the studied basin must not exceed a few hundreds kyr (duration of the Late Sarmatian), probably much less.

Based on the study by Görög (1992), a regional correlation is proposed here between the ramp carbonates and the neighbouring basinal deposits. The boreholes drilled in the Zsámbék Basin indicate that the Sarmatian deposits are 120 to 180 m thick; they are composed mainly of sandstones, clays and marls with some limestone interbeds. Sequence A is correlated with the Early Sarmatian deposits (E. reginum and E. hauerinum zones) and the lower part of the Late Sarmatian (S. austriaca zone). In the boreholes, these deposits are interpreted as shallow-marine (with a maximum depth of about 100 m), with variations in oxygenation and salinity and an upward shallowing trend. Sequence B is correlated with the uppermost Sarmatian deposits of the S. austriaca zone. These sediments, in the basin as well as on the margins, were formed in warm, shallow-water marine lagoons. In the cores, the boundary between sequences A and B is difficult to locate as it probably corresponds to a depositional surface. This observation indicates that the relative sea-level drop recorded on the margins was limited to some tens of metres at maximum, before the subsequent marine transgression (Sequence B); this is also in accordance with field observations:

- on the margins of the Zsámbék basin there is no major sedimentological change between Early and Late Sarmatian deposits, which are all represented by oolites, coquina beds and bryozoan-rich buildups;
- the erosive event between Units A and B created comparatively low-relief structures of a few metres.

The Sarmatian carbonate platforms are widespread throughout the Paratethys: Austria, Romania, Moldavia, Poland, Ukraine and Crimea (Pisera, 1996). West of the Zsámbék Basin, the Vienna Basin was studied intensively (Harzhauser & Piller, 2004a,b; Piller & Harzhauser, 2005; Harzhauser et al., 2006; Gross et al., 2007a; Schreilechner & Sachsenhofer, 2007; Sopková et al., 2007). The Sarmatian deposits have been subdivided into two main formations:

- The Early Sarmatian Holic Formation, continental in the north and changing into marine deposits in the south. It is composed mainly of
calcareous clays and marls, changing laterally along the margins into bryozoan–algal–microbialite buildups, limestones and conglomerates.

- The Late Sarmatian Skalica Formation, with various lithologies such as marls, siltstones, sandstones, bioclastic limestones and oolitic limestones (Kosi et al., 2003) associated withstromatolitic and foraminiferal buildups.

The Sarmatian stage has been considered as the TB 2.5 third-order cycle of Haq et al. (1988), between 13.6 and 12.7 Ma (Vakarcs et al., 1998). This age was revised by Harzhauser & Piller (2004b). These authors consider that the Sarmatian stage was a third-order eustatic cycle, between 11.6 and 12.7 Ma (Cycle TB 2.6 of Haq et al., 1988). This third-order cycle can itself be subdivided into two fourth-order cycles (400 kyr eccentricity components). In the proximal areas, Cycle LS-1 (E. reginum and E. hauerinum zones) comprises siliciclastic deposits and bryozoan–serpulid buildups, whereas Cycle US-2 is composed of mixed siliciclastic–oolitic deposits with nubeculariid buildups. In the Zsámbék Basin the situation is somewhat different: the proximal areas show abundant oolithic deposits from the Latest Badenian to the Latest Sarmatian. This study does not, however, document the upper and lower sequence boundaries of the Sarmatian deposits. The abundant siliciclastic sediments of Austria are a result of the Alps and the Carpathians being in the vicinity during their uplift (Harzhauser & Piller, 2004b; Harzhauser et al., 2006). Conversely, the Zsámbék Basin was far from the Alpine mountain belt and carbonate sedimentation consequently prevailed. In Austria as well as in Hungary, the Sarmatian deposits are organized in two major sedimentary cycles: the first is Early Sarmatian in age and the second is referred to as the ‘uppermost Sarmatian’. With the current state of knowledge, it is not possible to know without doubt whether the cycles are strictly coeval in both basins because of the lack of precise chronostratigraphic data, scarce information regarding the base and the top of the deposits in the Zsámbék Basin and potential tectonic control.

**Sediment composition**

**General features**

The most significant characteristics of the studied Sarmatian deposits are: (i) the conspicuous absence of pelagic fauna, especially planktonic foraminifera; (ii) the dominance of non-skeletal grains (peloids, micritized ooids, proto-oncoids and oncoids, aggregates and lithoclasts); (iii) the presence in Sequence A of a shallow-water benthonic fauna containing a limited number of foraminiferal genera (mostly miliolids and elphidiids) associated with bryozoans and relatively diverse ostracods and molluscs; (iv) the presence in Sequence B of a rather similar association, but...
with buildups composed of variable amounts of nubeculariids, bryozoans, microbialites, serpulids and red algae; (v) despite tropical to subtropical conditions, as suggested by ooids, peloids and foraminiferal assemblages (Boda, 1974b; Görög, 1992; Harzhauser & Piller, 2007), hermatypic corals, molluscs typical of coral reef environments and echinoids are conspicuously absent and red algae and larger benthonic foraminifera are rare (except S. austriaca and Borelis sp.); and (vi) minor amounts of detrital material occur in all sections. These features indicate that the carbonate factory was restricted to coastal lagoons, shoals and inner ramp. The ensuing carbonate grains were later transported and re-deposited towards the basin, onto the mid-ramp and the outer ramp.

According to Harzhauser & Piller (2007), the upper Sarmatian oolites are the only Miocene oolites in the entire Central Paratethys. However, in the Zsámébék Basin oolites already occur in the Late Badenian, as demonstrated by the Biatorbágy section, and in the Early Sarmatian.

Skeletal content

As in other Sarmatian basins, the organisms occurring in the Zsámébék Basin are limited to a small number of groups and species, but these are often represented by numerous individuals. Coralline (Lithoporella sp., Lithophyllum sp.) and dasycladacean (Acicularia spp., Cymopolia sp.) calcareous algae are relatively common (Boda, 1954, 1974c; Kátay, 1983).

Sixty-three species of benthonic foraminifera have been identified by Görög (1992) in three boreholes. The most abundant groups in the studied limestones are the miliolids, either as bioclasts or nuclei of oolites, and the nubeculariids which may even form sediments (Boda, 1979). Other genera (Elphidium, Spirolina, Rosalina and Ammonia) occur in variable amounts and Borelis shells are sometimes relatively numerous (Boda, 1959, 1970).

Bivalves and gastropods are the dominant groups of invertebrates, both in number of species (22 and 23, respectively) and volume (Boda, 1959), and accumulations of mollusc shells often occur within the bioclastic deposits. However, in the mostly calcareous facies of the samples studied, the relatively poor quality of preservation (moulds) of these predominantly primary aragonitic shells often precluded a more specific identification.

The serpulid worms, although not diverse (three species), are often abundant (Boda, 1959). The same is true for the bryozoans (four species), occurring mostly in small buildups. The oysters are relatively common and diverse (Tóth, 2004, 2008). Rare fish remains (teeth and otoliths) have also been found.

Buildups

Buildups have been found in Sequences A and B. In Sequence A they are rare and were observed only in the Páty and Gyúró sections. These buildups are dome-shaped with a flat base, about a decimetre high and up to 1 m wide (Fig. 18); they are composed almost exclusively of the encrusting bryozoan S. unicornis. Buildups are frequent in Sequence B (Fig. 19); they essentially developed in the distal part of the platform. In the proximal areas, as in the Biatorbágy section, they

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**Fig. 18.** Bryozoan–serpulid buildup (Páty quarry). The upper crust is made only of calcareous red algae, whereas the lower part consists mostly of bryozoan colonies ‘B’ with a small number of serpulid tubes ‘Sp’, accompanied by microbialites and bioclasts.
are limited to centimetre-wide to decimetre-wide nodules or bindstones around pebbles. In the distal parts, as in the Zsámbék, Sóskút and Gyúró sections, they generally form centimetre-thick carpets and centimetre-thick to metre-thick domes. The buildups are built predominantly by serpulid worms and bryozoans, although some of them are formed by serpulid tubes only. Coralline algae and encrusting foraminifera (nubeculariids: \textit{Sinzowella novorossica}) are sometimes associated and the presence of microbialite is often observed (Fig. 20A to C). Three species of serpulid worms (\textit{Hydroides pectinata}, \textit{Spirorbis heliciformis} and \textit{Serpula gregalis}) and one species of encrusting bryozoans (\textit{S. unicornis}) generally make up the bulk of the framework. Together, these invertebrates constitute mazes of tangled crusts leaving only rare and tiny cavities (Figs 18 and 19). Three other encrusting bryozoan species (\textit{Conopeum reticulum}, \textit{Cryptosula pallasiana} and \textit{Tubulipora} sp.) occasionally participate in the construction process but they are never abundant. It has been noted that species of \textit{Schizoporella} often develop multilamellar colonies thus forming small buildups (e.g. in the present-day Mediterranean; Cocito \textit{et al.}, 2000).

Carbonate buildups have often been reported from the Sarmatian of the Paratethys basins of Austria, Ukraine, Poland, Romania and Moldavia (Andrusov, 1936; Buge & Calas, 1959; Ghiurca, 1968; Kulichenko, 1972; Ghiurca & Stancu, 1974; Friebe, 1994; Pisera, 1996; Saint Martin & Pestrea, 1999; Boiko, 2001, 2004; Jasonowski \textit{et al.}, 2002; Sholokhov & Tiu nov, 2003; Harzhauser & Piller, 2004a,b; Harzhauser \textit{et al.}, 2006). The main framework builders are serpulid worms, bryozoans, coralline algae and microbial crusts, along with subordinate encrusting nubeculariid foraminifera. The associated biota is usually fairly diverse, including bivalves, foraminifera, ostracods and rare gastropods. The bioclastic material is also relatively abundant. Piller & Harzhauser (2005) distinguished two main types of carbonate bioconstructions. The Lower Sarmatian (= Volhynian for the Eastern Paratethys) buildups are characterized mainly by abundant serpulid agglomerates, dense microbialitic masses, numerous Rissoideae (\textit{Mohrensternia}) and oligospecific bivalve accumulations (\textit{Obsoletiforma}, \textit{Musculus}, etc.). Buildups from the Upper Sarmatian beds (= Bessarabian for the Eastern Paratethys) generally form small hemispherical lenses or extensive crusts with nubeculariids, red algae and bryozoans, associated with diversified mollusc shell accumulations. The carbonate buildups of the Zsámbék Basin are close to the second type.

\textbf{A seagrass originated material?}

Present-day seagrasses are common shallow-water components on the continental platform of most oceans. These marine phanerogams occur in a wide range of coastal environments, in temperate to warm waters. Most species are stenohaline, whereas others are either euryhaline, euhaline or polyhaline (Larkum & den Hartog, 1989; Jernakoff \textit{et al.}, 1996). The existence of seagrasses in the fossil record is, however, difficult to prove because of the scarcity of direct evidence. Nevertheless, their former presence can
sometimes be deduced from the occurrence of characteristic organisms such as calcareous algae, foraminifera, molluscs and ostracods (Brasier, 1975; Beavington-Penney et al., 2004; James & Bone, 2007; Moissette et al., 2007b).

Although the buildup-forming Sarmatian nubeculariids (Fig. 20B and C) are not seagrass indicators, the cosmopolitan encrusting miliolid *Nubecularia* is a common epiphytic foraminifera, especially in the Mediterranean and around Australia (Langer, 1993; James & Bone, 2007; Moissette et al., 2007b). The modern *Nubecularia lucifuga* is most prolific in seagrass beds at depths shallower than 10 m (Cann et al., 1988, 2002). In the material studied, frequent hooked and ring-like forms (Fig. 21) of the fossil endemic encrusting nubeculariid *S. novorossica* suggest that seagrasses may have been present (Friebe, 1994; Beavington-Penney et al., 2004). Specimens detached from their macrophyte substrates are sometimes accumulated in rock-forming quantity throughout the Paratethys (Gillet & Derville, 1931; Papp, 1974; Boda, 1979). It is possible to conclude, based on common occurrences of this nubeculariid, that seagrass communities were ubiquitous members of the shallow-water Sarmatian ecosystem.

Another typical epiphyte on seagrass leaves is the larger, disc-shaped, sessile foraminifera *Sorites* (Wright & Murray, 1972) found in Sarmatian marls west of the Zsâmbék Basin (Korecz-Laky, 1966). Although elphidiids, miliolids and cibicidids (Görög, 1992) do not live exclusively on seagrass leaves, their presence in the studied sediments is also indirect evidence of a fossil seagrass community (Semeniuk, 2001). The abundance of small grazer gastropods such as *Gibbula* and *Hydrobia* (mostly feeding on diatom films)
may also be used as indicators for the existence of seaweeds or seagrasses (Mazzella & Russo, 1989; Jernakoff et al., 1996). In addition, the occurrence in the studied material of frequent epiphytic ostracod genera like *Loxoconcha*, *Xestoleberis* and *Aurila* may suggest the existence of seagrasses in the Sarmatian sea (Puri et al., 1969; Iryu et al., 1995; Saint Martin et al., 2000; Stone et al., 2000). The presence of seagrass meadows in the region may have played an important role in the stabilization of ooid shoals (Hine, 1977).

### Palaeoenvironments

Even if oolitic deposits are associated generally with a sparse flora and fauna (Ball, 1967; Halley et al., 1977; Hine, 1977; Burchette et al., 1990; Ginsburg, 2005), prevailing conditions are normal marine and a typical tropical biota can be found in lateral equivalents (e.g. in the Persian Gulf; Evans, 1966; Gischler & Lomando, 2005). In the Zsámbék Basin this biota is either uncommon or absent, implying that anomalous environmental conditions may have been present. Factors likely to influence carbonate production in sea water include oxygen availability, temperature, alkalinity, salinity, nutrient levels and light intensity (Mutti & Hallock, 2003; Halfar et al., 2006).

Few data concerning sea water temperatures and alkalinity are available for the studied basin. An elevated alkalinity was proposed by Pisera (1996) to explain the widespread development of microbial buildups during the Sarmatian. Based on geochemical investigations, temperatures of about 15 °C were estimated for the Early Sarmatian and between 15 and 21 °C for the Late Sarmatian. Tropical conditions correspond to a mean annual temperature of at least 22 °C and subtropical temperatures generally range between 18 and 22 °C (Mutti & Hallock, 2003). Nevertheless, in recent analogues, such as for example the Persian Gulf, temperatures were recorded in the 13 to 32 °C interval and salinity fluctuates between 37‰ and 42.5‰ (Gischler & Lomando, 1997). In the Gulf of California coral reefs develop in areas where temperatures range from 18 to 31 °C, with average salinities of 35.25‰ and low chlorophyll a levels (Halfar et al., 2006). In the Tengelic-2 borehole of Central Hungary, palynological investigations concluded that a progressive cooling occurred during the Sarmatian, with mean annual temperatures decreasing from around 20 °C in the Badenian to 16 °C in the Sarmatian and mean annual precipitations dropping from about 1550 to 1100 mm year⁻¹ (Jimenez-Moreno et al., 2005). These results are in accordance with the study of Erdei et al. (2007) on fossil plant assemblages. This information suggests that sea water temperatures during the Sarmatian were around the lowest limit for coral growth, in accordance with a palaeolatitudinal position around 45° N (Popov et al., 2004). According to Tucker (1985) and Piller & Harzhauser (2002), the development of calcrete crusts indicates a semi-arid climate.

Only ooids and peloids were formed, as during the Holocene, in limited settings like the warm temperate waters of the Mediterranean coast of Egypt (El-Sammak & Tucker, 2002), Tunisia, Libya (Fabricius & Berdau, 1970) and Greece (Richter, 1976; Milàn et al., 2007). The conditions generally required for the formation of ooids, especially tangential ones, are calcium carbonate supersaturation and sea water agitation (Davies et al., 1978; Hearty et al., 2006). Seasonal changes from saline to hypersaline conditions and increased water energy produced by restriction of flow through narrow passages between shoals can also favour the formation of ooids (Hearty et al., 2006; Pedley et al., 2007; Čadjenović et al., 2008). In the outcrops studied, lagoonal settings with temporally and spatially fluctuating salinities are indicated by ostracod and foraminiferal associations but these are restricted to Sequence B in some of the sections. In the boreholes of the Zsámbék Basin, salinities of 18‰ to 25‰ were inferred by Görög (1992) or calculated between 15‰ and 43‰. Even though the Sarmatian deposits classically are regarded as formed in brackish-water environments (Papp, 1956; Boda, 1974a; Görög, 1992), both sedimentary and biological compositions (*Spiroolina*, *Borelis*, bryozoans, *Cnestocythere*, etc.) indicate dominant marine conditions, as also demonstrated for the Vienna Basin by Harzhauser & Piller (2007) or for the whole Paratethyan area by Pisera (1996). Fluctuating salinities reveal the evolution of a complex oceanographic domain. Evidence for marine influx during the Sarmatian comes from frequent diatomite deposits containing rich assemblages of marine diatoms and silicoflagellates in Austria (Schütz et al., 2007), Croatia (Galović & Bajraktarević, 2006), Romania (Saint Martin & Saint Martin, 2005) and Hungary (Hajós & Réháková, 1974; Hajós, 1976, 1986). Episodes of relative isolation alternate with periods of oceanic incursions.

The preserved biological content, among which is scarce red algae, together with the absence of
corals and echinoids also suggests nutrient-rich waters, generally considered as detrimental to skeletal-dominated carbonate platform development (Hallock & Schlager, 1986; Mutti & Hallock, 2003; Chazottes et al., 2008). Indeed, opportunistic foraminifera (miliolids, *Elphidium*, nubeculariids) and suspension-feeding invertebrates are dominant, with molluscs such as *Modiolus* (Officer et al., 1982; Peterson & Heck, 1999, 2001) associated with bryozoans and serpulid worms. This nutrient-rich water hypothesis is in accord with the: (i) presence of constant continent-derived siliciclastics in the carbonate sediments; (ii) semi-enclosed character of the basin, isolated from the open sea, thus favouring the accumulation of nutrients originating from the hinterland; (iii) poorly diversified fauna found in the material from boreholes drilled in the central part of the basin (Jámbor, 1974; Görög, 1992), suggesting that the whole water column (0 to 100 m deep) was affected by the same trophic conditions; (iv) elevated precipitations (Jimenez-Moreno et al., 2005); (v) frequent occurrence of sponge spicules (Schütz et al., 2007), diatoms and silicoflagellates (Hajós & Řeháková, 1974; Hajós, 1976, 1986; Galović & Bajraktarević, 2006; Schütz et al., 2007) and alginite levels (Bohn-Havas, 1983), all indicative of enhanced primary productivity; (vi) abundance of organic-rich facies in several boreholes of the region; and (vii) frequent microbial crusts in many buildups. Nevertheless, other typical features of nutrient-rich waters, such as macroalgae or bioeroders, have not been found (Mutti & Hallock, 2003; Halfar et al., 2006; Chazottes et al., 2008).

It has also been suggested that widespread ooids (together with microbialites) may be a response to biological mass extinction events (Calner, 2005). In the Paratethys, the normal-marine Badenian fauna and flora (Harzhauser & Piller, 2007; Moissette et al., 2007a). A sharp transition to the Sarmatian deposits that display a strongly impoverished fauna and flora is seen above (Boda, 1974a; Görög, 1992; Harzhauser & Piller, 2007). The impoverished marine fauna and flora of the Sarmatian may thus be explained by a combination of several factors: a global sea water cooling, a pronounced isolation from the Mediterranean, promoting the accumulation of nutrients in shallow and semi-enclosed basins, and variable salinity conditions (from brackish to hypersaline). In such a setting, oolitic production could develop because of calcium carbonate supersaturation, sufficient warm sea water temperatures and wave agitation, but not the distinctive tropical to subtropical faunal and floral assemblages.

**CONCLUSION**

The Sarmatian deposits of the proximal areas of the Zsámbeök Basin are composed of carbonates with a minor amount of siliciclastics. This feature is unique, as in other basins of the Central Paratethys carbonates developed only during the Late Sarmatian. The dominant components are non-skeletal grains and ubiquitous molluscs and benthonic foraminifera. These carbonate rocks are organized into two major depositional sequences separated by a regional erosional surface:

- **An Early to Late Sarmatian sequence** (*Elphidium reginum*, *Elphidium hauerinum* and lower part of the *Spiroolina austriaca* zones) composed of aggrading–prograding ooid and bioclastic subaqueous dunes, deposited on a low-angle ramp; the material was issued mainly from lagoons and inner ramp zones, then redistributed from the mid-ramp to the basin; rare bryozoan buildups also occur.

- **A Late Sarmatian sequence** (upper part of the *Spiroolina austriaca* zone) composed of prograding ooid deposits with abundant serpulid–microbial–bryozoan–nubeculariid buildups, deposited in lagoonal settings with fluctuating salinity; winds and waves controlled the sedimentation.

Even if the palaeoenvironmental conditions have changed in detail through time in the Zsámbeök Basin, the prevailing conditions during the deposition of the Sarmatian carbonates were supersaturation in carbonate content, wave agitation, warm temperate sea waters, fluctuating salinities, possible nutrient concentrations leading to mesotrophic to eutrophic conditions and perhaps high alkalinity. The ‘abnormal’ marine conditions leading to such peculiar carbonate deposits during the Sarmatian are coeval with a dramatic isolation of the Paratethys from the Indian Ocean and the Mediterranean.

**ACKNOWLEDGEMENTS**

The field research connected with this study was funded by common grants from the French CNRS/Hungarian Academy of Sciences, from the French Ministry of Foreign Affairs/Hungarian Ministry of Education and from the Hantken Foundation, Budapest. At the University of Lyon, UMR 5125,
Paula Desvignes prepared most of the original material for this study. At the Natural History Museum of Paris, UMR 5143, thin sections were made by Michel Lemoine. During fieldwork, Simona Saint Martin helped us collect some of the palaeontological specimens. Mathias Harzhauser, an anonymous reviewer and Sedimentology editors David J. Mallinson and Peter K. Swart are thanked for their constructive comments on an earlier version of this paper.

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