

Mykolaiv Sands in Opole Minor and beyond: sedimentary features and biotic content of Middle Miocene (Badenian) sand shoals of Western Ukraine

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Wysocka A., Radwański A. and Górka M. (2012) – Mykolaiv Sands in Opole Minor and beyond: sedimentary features and biotic content of Middle Miocene (Badenian) sand shoals of Western Ukraine. *Geol. Quart.*, **56** (3): 475–492, doi: 10.7306/gq.1034

The Mykolaiv Sands are a huge lithosome of Middle Miocene (Badenian) age, accommodated within the Fore-Carpathian Basin in the Western Ukraine. Typically developed in the area of Opole Minor, it spreads across adjacent regions of Opole to cover an area of about 1300 km². The varied sedimentary structures and ubiquitous burrows, indicate their development as a stack of sand shoals or related bodies, up to a few tens of metres thick, some of which temporarily reached sea level. Amidst the shoals, storm scours intermittently formed channel-like infills, some with residual lags at the base. The reversed density stratification and/or an increasing gravity gradient involved mass movements, some of which may have been triggered by seismic shocks focused at the shore or the adjacent hinterland of Podolia and Volhynia. Special attention is paid to the diverse fossils, all taphonomically filtered (aragonite shells and chitinous carapaces being lost), but which locally are mass-aggregated. They typify particular sand sets/bodies, to form allochthonous assemblages, some members of which (the cirripedes *Scalpellum* and *Creusia*, the shark *Hemipristis*, the ray *Myliobatis*) are newly recognized in the Ukrainian part of the Fore-Carpathian Basin. The others enrich considerably the faunal content of the Middle Miocene (Badenian) Paratethyan basins, either in terms of taxonomic diversity, or the eco-taphonomy of selected taxa (the starfish *Astropecten*, diverse echinoids). The whole faunal content of the Mykolaiv Sands may owe its profuse development to the global Middle Miocene Climatic Optimum of early Badenian age.

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Key words: Western Ukraine, Middle Miocene (Badenian), eco-taphonomy, burrows, depositional structures, sedimentology.

INTRODUCTION

The enormous accumulation of the Middle Miocene (Badenian) Mykolaiv Sands in Western Ukraine has long been known (Niedzwiedzki, 1879; Hilber, 1882; Łomnicki, 1897, 1898; Jahn, 1937; Malicki and Jahn, 1937; Teisseyre, 1938; Pazdro, 1953; Kudrin, 1966; Wysocka and Jasionowski, 2006), but never systematically described. This lack of interest has supposedly been caused by the paucity, or absence, of body fossils which occur abundantly in other coeval sands spreading widely throughout Western Ukraine. The sand-mass in question, typically developed around the small city of Mykolaiv (south of Lviv), situated near the valley of the Dnister River in the south, extends northwards as far as the vicinity of Lviv (Fig. 1). In their southern part, near Mykolaiv, the sands are poorly exposed along the slopes of gentle hills, and are covered by arable soil or forested, elsewhere. Their study has involved access to many commercial sand-pits or quarries established in

recent decades. When the present authors started with their investigation (Radwański and Wysocka, 2001), it appeared that the Mykolaiv Sands contained a well-nigh inexhaustible spectrum of sedimentary structures, both of physical and of biogenic origin. Moreover, their content of body fossils turned out to be not as scarce as thought formerly (see Radwański *et al.*, 2012).

The Mykolaiv Sands, as an informal lithostratigraphical unit, was distinguished by Petryczenko *et al.* (1994, fig. 2) and, as such, is used in the present paper.

REGIONAL SETTING

The Mykolaiv Sands extend from the southwestern margin of the East European Platform to border the tectonically active Carpathian Foredeep (Fig. 1). They rest upon a Laramide basement of Upper Cretaceous (Maastrichtian) marls, the to-

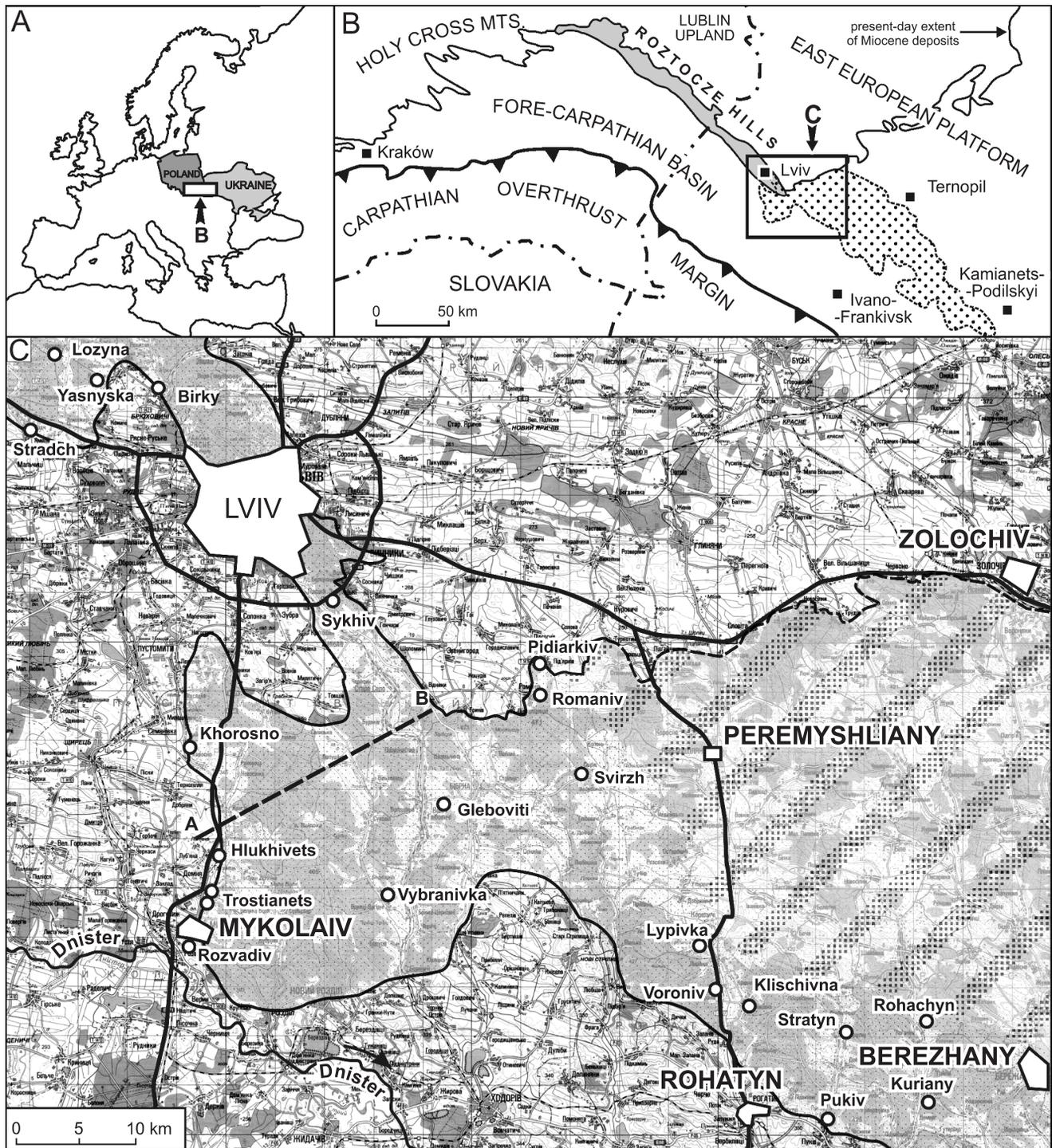


Fig. 1. Regional location of the Mykolaiv Sands studied

A – general setting of the region studied (B) in Europe; B – part of the Fore-Carpathian Basin in Poland and Western Ukraine, to show the Middle Miocene (Badenian) sequences of the Roztocze Hills (shaded) and Opole regions (dotted); indicated is the present-day extent of Miocene deposits upon the East European Platform; C – topographic map of the Opole Minor region (rectangled in Fig. 1B), to show the extent of the Mykolaiv Sands (shaded) and their key exposures; hachured is the area beyond the well-defined sands in the Middle Miocene (Badenian) sequence, and carpeted by a Quaternary cover (*cf.* Kudrin, 1966); A–B line of section in Figure 2

pography of which was sculpted by Paleogene erosion and denudation. The resultant pre-Miocene relief, being locally exposed today, is estimated at up to, or slightly over, one hundred metres (Pazdro, 1953, p. 26). The depressions in this were filled more or less completely with the Mykolaiv Sands, the

thickness of which ranges, consequently, from zero to one hundred metres.

The sequence overlying the Mykolaiv Sands, that is the red-algal (lithothamnian) limestones, produced in Western Ukraine a regional key-horizon (the Mid-Lithothamnian Horizon of Alth, 1850 and many subsequent authors). In places

where the Mykolaiv Sands are absent, these limestones rest directly upon the Upper Cretaceous basement. On the other hand, the regionally uniform sequence of Mykolaiv Sands differs from other sand bodies of the Lviv region (Łomnicki, 1897, 1898; Wysocka, 2002), as well as of sand aprons on the Medobory Range to the east (Hilber, 1882; Radwański *et al.*, 2006).

In geographical terms, the region of the typical occurrence of Mykolaiv Sands has been specified as Opole Minor (in Polish: Opole Mniejsze, see Pazdro, 1953), to distinguish it from other parts of the Opole regions. Nevertheless, in the present paper, the extent of the Mykolaiv Sands is greater than the extent of Opole Minor, covering some 600 km² to include northerly the region of Lviv, classified formerly as the Roztocze Hills (Radwański and Wysocka, 2001; Wysocka, 2002). Together with a part of the Dnister Opole, also included herein, the entire extent of the Mykolaiv Sands attains an area of about 1300 km² (see Fig. 1).

STRATIGRAPHICAL AGE

Although the Miocene stratigraphy of Ukraine is disputed, there is a general agreement to locate the Mykolaiv Sands and their biotic content in the lower Badenian (see Petryczenko *et al.*, 1994; Peryt and Peryt, 1994; Harzhauser *et al.*, 2003; Kroh, 2005, 2007; Radwański *et al.*, 2006, p. 99).

The Mykolaiv Sands is thought coeval with the classical Korytnica sequence in Poland (see Bałuk and Radwański, 1977; Radwański *et al.*, 2006), as well as with a part at least of the Badenian stratotype at the Baden-Sooss section in the Vienna Basin (see Rögl *et al.*, 2008). Less obviously the foraminiferal (lagenid) ecozonation of the Central Paratethys may be applied to the Mykolaiv Sands, though this is not clearly compatible with the calcareous nannoplankton dating of the Polish part of the Fore-Carpathian Basin (see Rögl and Brandstätter, 1993, pp. 142–144).

OVERALL LITHOLOGY OF SANDS

The petrographic content of the Mykolaiv Sands is very monotonous, being composed of quartz with variable but minor admixtures of glauconite, clay minerals (illite and/or

folioides), as well as calcareous mud and bioclasts. All these accessories may locally dominate, to form intercalations of sandy marl or limestone. The clay content, when moistened, gives rise to a gray-greenish hue of variable extinction, in places reminiscent of glauconite, true grains of which occur solely in the pure sand. Most of the layers, regardless to their thickness which ranges from centimetres up to ten metres at Sykhiv, are more or less unconsolidated.

All the bioclasts are calcitic, aragonitic ones having been completely leached during diagenesis. Moreover, the larger bioclasts are heavily armoured with sand grains due to pressure-solution (see Radwański and Wysocka, 2001; Radwański *et al.*, 2012).

The calcite-cemented sand layers appear in particular parts of some sections (e.g., at Stratyn), and their structural and biogenic content allows interpretation as beachrock (Radwański *et al.*, 2012).

A diagenetic supply of silica is indicated by the preservation, in unconsolidated quartz sands, of silicified wood fragments of variable shape and size (see below). Not discussed herein are local occurrences of compact quartzites, used as building materials a century ago, and interpreted by Pazdro (1953) as having formed *via* silica supply through tectonic fissures.

THE THICKNESS OF SANDS AND THEIR ACCESSIBILITY

The thickness of the Mykolaiv Sands, nowhere exposed in total, has been estimated as up to several tens of metres (Łomnicki, 1897, p. 35), up to 40 m, rarely to 90 m (Teisseyre, 1938, p. 115), or up to 60 m (Pazdro, 1953, p. 35). But, if post-Miocene block-faulting tectonics is taken into account (see Pazdro, 1953, fig. 9; and Fig. 2 herein), these figures must be reduced to almost a half. That is, 20 to 45 metres at maximum.

At present, the new sand exposures show sections up to 20 metres thick (Fig. 3), resulting from the logistics of quarrying, groundwater seepages included (e.g., at Stradch). Where a thicker sequence was met by deeper quarrying, its lower parts are now abandoned and covered with scree (e.g., at Stratyn, see Radwański *et al.*, 2012).

In most sections studied, the exposed sequence of the Mykolaiv Sands represents its terminal part, topped by the

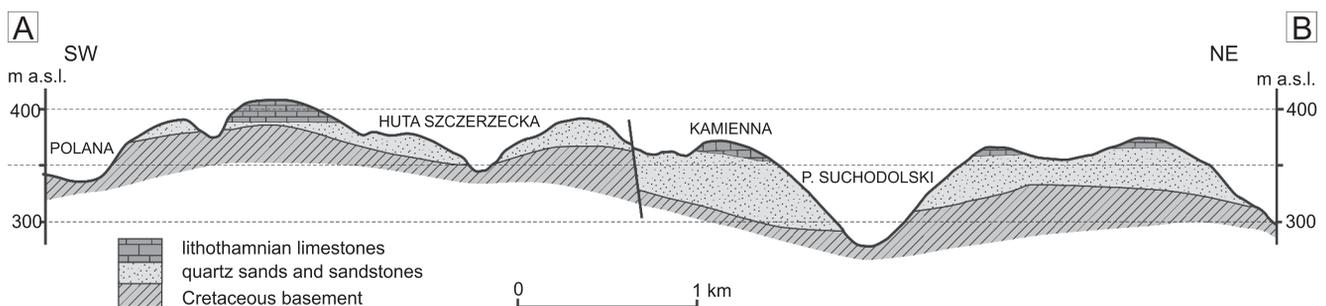


Fig. 2. Generalized section through Opole Minor (A–B line in Fig. 1), to show the Middle Miocene (Badenian) sequences overlying the Cretaceous basement; adapted from Pazdro (1953, fig. 9)

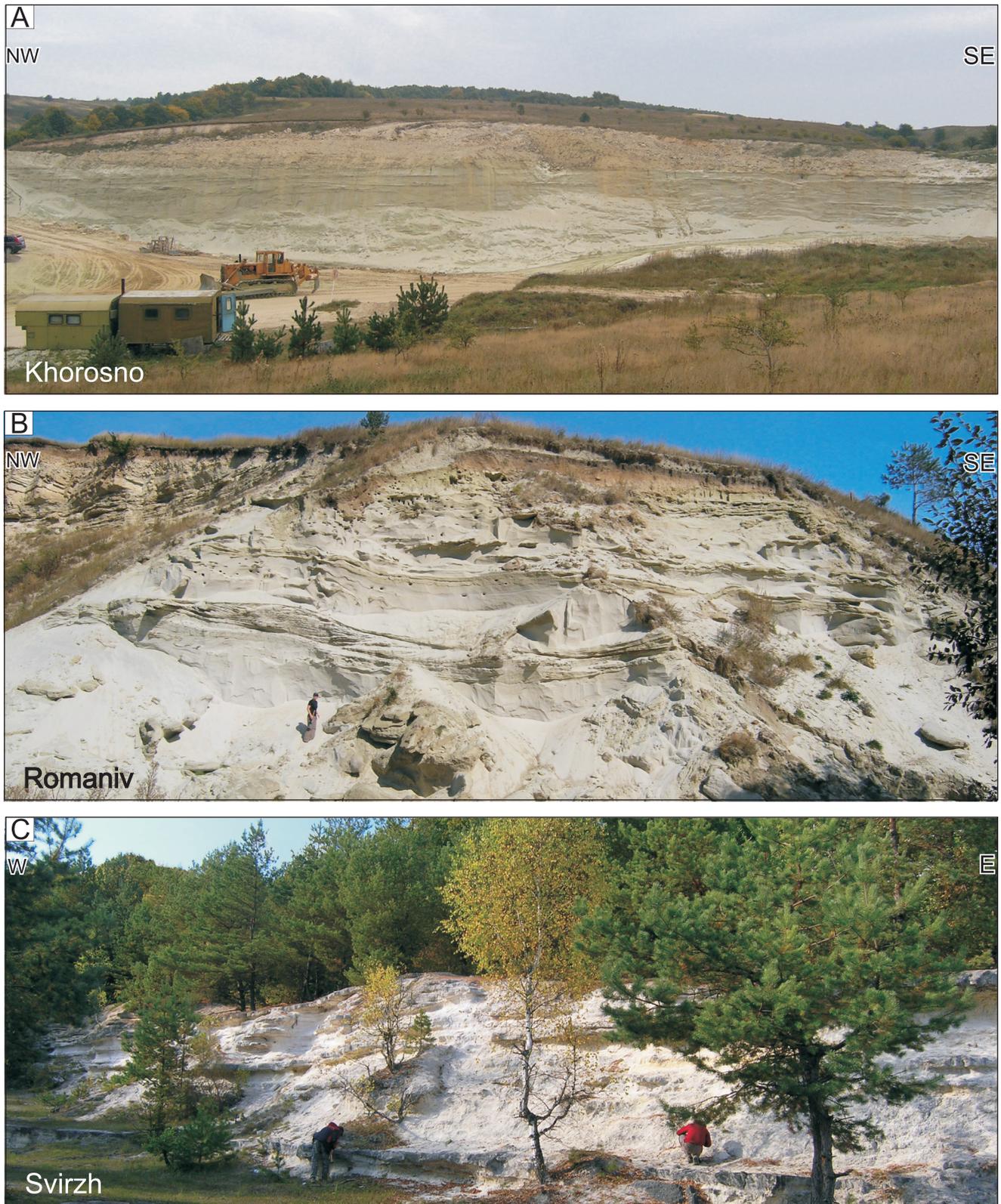


Fig. 3. Typical exposures of the Mykolaiv Sands

A – Khorosno – intense quarrying: the entire hill is to be exploited; **B** – Romaniv – local quarrying along a stream escarpment;
C – Swirzh – local quarrying by the road running through a forested hill

lithothamnian limestones or locally by the Ratyn Limestones (see Peryt and Peryt, 1994). Only one section, at Gleboviti near Bibrka, carries both the lithothamnian limestones at the top and *in situ* coniferan stumps (silicified) indicative of preserved ground level (Radwański and Wysocka, 2001). The thickness of that section, measuring some 12 metres, is reduced, having accumulated on a hummock of the Cretaceous basement that was named the Bibrka-Mykolaiv range (Teisseyre, 1938; Pzdro, 1953).

REVIEW OF SEDIMENTARY FEATURES

The Mykolaiv Sands comprise a complex and variable array of units/sets, most stratified, but some unstratified. Within particular units/sets, both depositional and deformational sedimentary structures are present, of variable height/thickness, and commonly burrowed. The most common types of structures are reviewed herein, to demonstrate their diversity, frequency in a unit/set, and relation to the adjacent strata in a section (Table 1 and Fig. 4).

Directional structures are not constantly oriented. Their range of directions, regardless to the size of units/sets (Fig. 4A–D) includes all sectors except the north. The largest cross-sets, with straight or concave foreset laminae tend to be oriented south-westerly (Fig. 4A).

Within the sand-pit exposures accessible, particular units/sets change laterally into, or interfinger with, the sandy units/sets of other structures across very short distances. Change also takes usually place vertically, where particular units/sets are stacked one above the other in variable successions, and no preferred trend is seen through the whole sequence of the Mykolaiv Sands.

The sedimentological data recognized allow interpretation of the depositional bodies as migrating megaripples of various kinds, sand bars, slumps, and/or delta-slope bodies. All of these are of a varying size/extent, accommodate with, or complementing, the bottom morphologies of formerly deposited bedforms. On a regional scale, the particular units/sets of sand bodies are therefore irregularly distributed, and the vertical sequences differ markedly from one section to an other.

The biogenic structures, being burrows of various kinds, are present in all units/sets of each section, except for the largest cross-bedded or structureless sand bodies.

The deformational structures are recognized to have formed by various mechanisms (Table 1), some caused, or triggered, by seismic shocks.

GENERAL BIOTIC CONTENT OF THE MYKOLAIV SANDS

THE FLORAL CONTENT

Apart from the ubiquitous marine red-algae *Lithothamnium* and its allies, forming either nodules or detritus in the sands, and becoming rock-building in the limestones overlying the

sands, locally there are terrestrial plant remains. Although sporadic, they are diverse, represented by coalified detritus, locally fine-grained, compressed fragments in casts, as well as smaller or larger pieces of silicified driftwood, all undeterminable, but the latter occasionally bored by *Teredo* (see Łomnicki, 1897, 1898).

The new findings include examples of driftwood completely crumbled away, but the hollow casts containing sandy, internal moulds (steinkerns) of tubes of teredinid bivalves (Fig. 5E).

There are rare, spectacular silicified stumps of taxodiacean conifers, over one metre in diameter, and preserved *in situ* at Gleboviti (see Fig. 5F; Radwański and Wysocka, 2001, fig. 4 and pl. 1, fig. 1). Large, rounded boulders of such wood occur also at Stradch.

There are, too, scattered small pieces of amber (succinite), long noted since a report by Kner in 1851 (see Łomnicki, 1897; Srebrdolski, 1980).

THE FAUNAL CONTENT

All recognized faunal elements in the Mykolaiv Sands (see Figs. 5 and 6) belong to open-marine taxa, living in waters of full salinity, as first noted by Niedźwiedzki (1879) and Hilber (1882). Oligohaline and/or brackish elements are lacking. Of terrestrial groups, no fossil fragments (like bones, teeth, antlers, etc.) have been found. All preserved biota are calcitic, aragonitic and/or chitinous ones having been totally removed during diagenesis. Some of the latter can, however, be recognized by the more or less cemented burrows constructed, and preserved, in loose sands (of sea anemones, polychaetes, crabs and shrimps, echinoids, and holothurians – see Table 1). Exceptionally preserved also are the sand-built internal moulds (steinkerns) of some bivalves, either of their shells, or their siphonal tubes, as well as the calcitic collars of such tubes (see below).

The calcite-shelled biota, sporadic or missing in some layers, become very common in others, to produce local mass-occurrences. This concerns primarily the echinoderms, both echinoids and starfish (Fig. 5A–D), the scanty former reports of which (Niedźwiedzki, 1879; Hilber, 1882; Łomnicki, 1897, 1898; Szörényi, 1953; Kudrin, 1957a; Kroh, 2005) contrast with their ubiquitous recognition presently (Radwański and Wysocka, 2001).

Of the calcitic bivalves, the most common are the isolated valves of small scallops (?various species) and oyster detritus. The latter is derived from a smooth-shelled small species, regarded as endemic, *Neopycnodonte leopolitana* (Niedźwiedzki, 1909), and discussed formerly (Radwański and Wysocka, 2004, pp. 390, 391). The large scallop *Macrochlamis nodosiformis* (de Serres in Pusch, 1837) is not uncommon at Khorosno; its taxonomy follows that one recently revised by Mandić (2004).

The cirripedes, apart from a single report of *Poecilasma* from Pidiarkiv (Reuss, 1864, pl. 2, fig. 12), classified by Withers (1953, pp. 340, 341) as *Trilasmis* (*Poecilasma*) *miocaenicum* (Reuss, 1864), are represented by numerous *Scalpellum* at Khorosno, and rarely by the coral-inhabiting

Table 1

The main bodies of the Mykolaiv Sands, and their facies significance

	Structures	Characteristics	Interpretation
Positional (D)	large-scale tabular cross-stratification, occasionally in form of clinoforms D_x	medium- to coarse-grained sands; average thickness of single sets about 2–4 m, maximum up to 10–15 m; forest laminae straight to sigmoidal	migration of straight-crested bars or progradation of a delta slope; high-energy shallow-water environment
	trough cross-stratification D_t	medium- to coarse-grained sands; set thickness from 10 to 50 cm	migration of curved-crested ripples; high-energy shallow-water environment
	ripple cross-lamination D_r	fine-grained sands; heights of individual ripples range between 2 and 10 cm; dominant asymmetrical and climbing (ripple laminae-in-phase and ripple laminae-in-drift) ripples, occasionally wavy and flaser lamination	migration of wave and wave-formed current ripples; shallow-water environment, (?) up to intertidal
	plane bedding D_p	various sands; thickness of sets rarely exceeds 10 cm	lower- or upper-stage plane beds; low- to high-energy shallow-water environment
	large-scale scours D_s	large elongated scours filled with fine-grained, well-sorted sands; depth up to 10 m, widths range up to 20 m; concave sharp and erosional bottom surface; basal part massive, top parts with traces of lamination and numerous folds and diapirs	grain flow in the form of underwater slump-scours; sediment movement caused by overloading of slope, rapid drawdown and destruction of frontal part of a delta body, and/or by seismic shock
	channel-like fills D_{ch}	channel-like elongated forms filled with massive fine- to coarse-grained sands and/or organodetrital material; sharp concave lower boundaries, depth up to 3 m, width to 5 m	storm surge channels, locally filled by lag deposits
	Biogenic (B)	individual burrows B_b	syn- or post-depositional activity of shrimps (<i>Callinassa</i>) or crabs (<i>Ocypode</i>), as well as undetermined sea anemones, bivalves and holothurians
maze of “burrow-ghosts” of various size, totally blurring primary depositional structures B_m		total destruction of depositional structures, formed by long-term activity of abundant bottom dwellers	
Deformational (F)	slump (fold and diapir) structures F_f	highest parts of scour infills, vertical or overturned anticlines and synclines, commonly detached, with strongly deformed flexure zones; up to 2 m height	caused by collapse of large-scale bars or delta slopes and/or by seismic shock
	convolute bedding F_c	small-scale folds underlain or overlain by non-deformed deposits; deformed layer thickness up to 30 cm; anticlinal parts are steep and chevron-like, synclinal are flat	result of reversed density gradient or sediment liquefaction; caused by overburden of overlying deposits, seismic shock and/or movement of liquefied sediment
	pseudonodule structures F_p	disturbed bedding in form of ovate or spherical masses surrounded by massive sands	fluid-loss structures, produced by escaping water, breaking upwards through primary lamination; caused by gravity mass movement or deformational shear of currents
	structureless F_s	sands completely devoid of any sedimentary structures; bodies up to 15 m thick	homogenisation caused by rapid sedimentation, total bioturbation, redeposition, and/or liquefaction

Creusia at Stratyn, both as yet unknown from the Ukrainian part of the Fore-Carpathian Basin, and discussed below.

The bryozoans, apart from being present as fine detritus in many layers (e.g., at Romaniv), are represented also by well-preserved, large colonies (at Khorosno, Pukiv); they are presently being studied by Dr. Kamil Zágóršek, of the National Museum at Prague, Czech Republic.

Shark teeth are common, occurring singly in some sections (e.g., at Gleboviti, Khorosno, Pidiarkiv, Berezhany) and reported earlier (Łomnicki, 1897; Kudrin, 1957b). At Khorosno, there are associated toothplates of the rays (Batoidei) *Myliobatis*, unknown formerly from the Ukrainian part of the Fore-Carpathian Basin.

ECO-TAPHONOMY OF FOSSILS

As regards the eco-taphonomy of the Mykolaiv Sands biota, their mode of preservation is diverse. Biota are excep-

tionally preserved, in life position, as in the stumps of taxodiacean conifers at Gleboviti, and some animals. The latter include detritus-armoured tubes of *Diopatra*-type polychaetes, and sandy moulds of the bivalve *Panopea*, the environmental significance of which is discussed below.

Except for these cases, all animal fossils were hydrodynamically reworked, to be either dispersed randomly in a sand layer, or accumulating in certain layers. In the case of echinoderms, studied separately (Radwański and Wysocka, 2001), it is even possible to recognize whether entombment took place in life (*in vivo*), or after death (*post mortem*).

In the case of the starfish *Astropecten forbesi* Heller, 1858, their preservation as complete skeletons (Fig. 5A, B), locally fragmented (at Gleboviti, Yasnyska, Khorosno), indicates rapid burial of freshly dead specimens. Some such specimens, within storm layers (tempestites) at Gleboviti, appear in a position typical of mortal cramp (see Fig. 5A) which suggests their burial while still alive (that is, *in vivo*). The same is inferred for the endobenthic echinoids *Echinocardium leopolitanum*

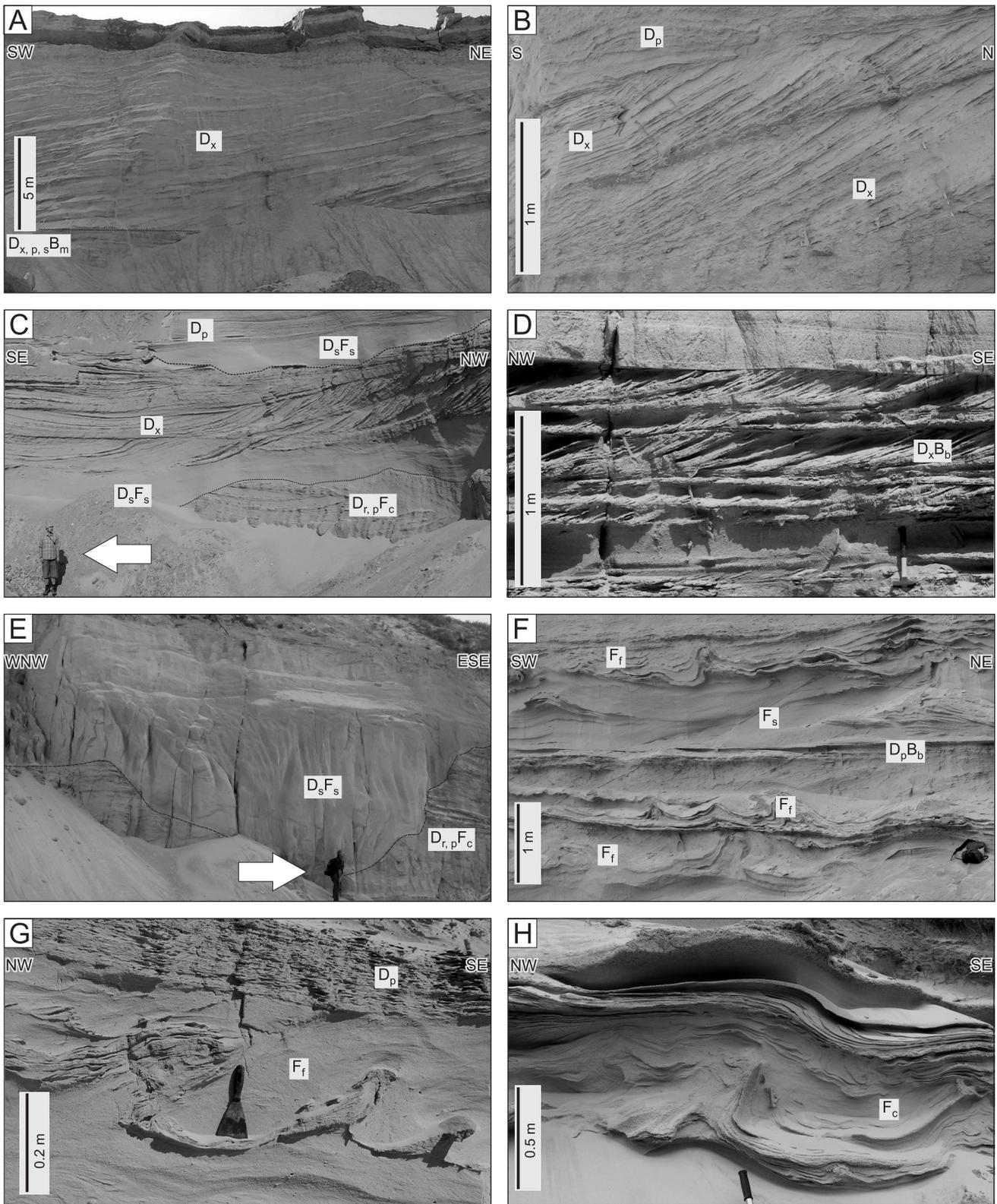


Fig. 4. Sedimentary structures of Mykolaiv Sands

A – progradational set of large-scale tabular cross-stratification, downlapping on plane-stratified sands (Sykhiv); **B** – cosets of tabular cross-stratification (Khorosno); **C** – channel-like in fills (base outlined) cut into cosets of tabular and trough cross-stratified sands (Khorosno); **D** – cosets of tabular cross-stratification with single *Ophiomorpha* burrows (Hlukhivets); **E** – large-scale cross-section of a giant scour filled with structureless sands (Hlukhivets); **F** – cosets of synsedimentary deformed layers (Khorosno); **G** – small-scale fold deformations overlain by non-deformed deposits, to show that south-inclined anticlinal parts are steep whereas synclines are flat (Romaniv); **H** – close-up of convolute bedding (Romaniv); for explanations see [Table 1](#) and [Figure 8](#)

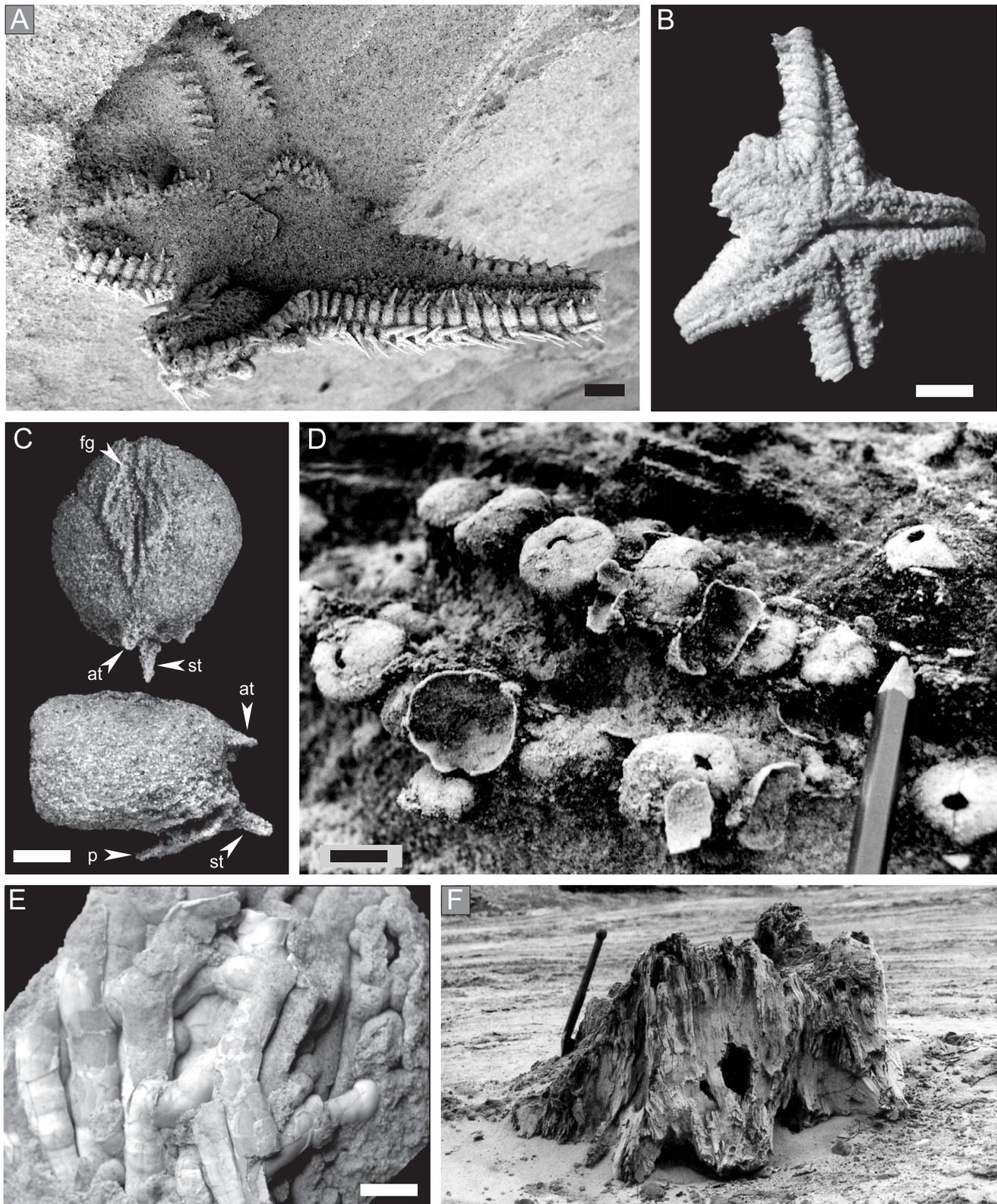


Fig. 5. Eco-taphonomic variants of fossils occurring in the Mykolaiv Sands

A – starfish *Astropecten forbesi* Heller, 1858, buried *in vivo* in a storm layer at Gleboviti (field photo); **B** – another specimen of starfish *Astropecten forbesi* Heller, 1858 (oral view) from a storm layer at Gleboviti; **C** – echinoid *Echinocardium leopolitanum* Radwański and Wysocka, 2001 (top and side views), buried *in vivo*, with fully preserved spine canopy, to show a spine array: fg – frontal groove terminated with apical tuft spines (folded), at – anal tuft spines, st – subanal tuft spines, p – locomotory spines; storm layer at Gleboviti; **D** – current-oriented (imbricated), naked tests of *Echinocardium leopolitanum* Radwański and Wysocka, 2001, in a tabular (diagonal) cross-bedded set at Gleboviti; **E** – sandy internal moulds (steinkerns) of terebrid bivalves which bored into a timber log (disintegrated), from Romaniv; **F** – large, silicified stump of a taxodiacean conifer (field photo) preserved *in situ* at the base of the Middle Miocene (Badenian) section at Gleboviti; scale bar is 1 cm; shovel on [Figure 5F](#) is about 0.5 m

Radwański and Wysocka, 2001, which are commonly preserved with a complete spine canopy (see Fig. 5C) when exhumed, and re-buried by a storm sand-sheet. In the case of current deposition, the tests are spineless, devoid of canopies, thus having been buried evidently after death and partial decomposition of their skeletons. Such a mode of preservation is typical in planar cross-bedded layers (in sets with straight foreset laminae) where the echinoid tests are usually current-oriented (imbricated, see Fig. 5D).

In terms of environmental significance, the Mykolaiv Sands and in the basal part of the overlying limestones (see Figs. 7 and 8) include fossils which, using uniformitarian criteria, indicate extremely shallow subtidal to intertidal life conditions. At Khorosno, there are vertically preserved tubes, heavily armoured with shell detritus (see Fig. 7B₁), comparable to those of the present-day polychaetes of *Diopatra* type. They reinforce the tubes (see Myers, 1970, fig. 1c; adapted in Fig. 7B₂ herein) to protect them against a “to-and-fro” motion of tidal water and its sediment load (see also Fig. 7B₃).

At Gleboviti, the uppermost parts of siphonal tubes of the bivalve genus *Stirpulina* Stoliczka, 1870, or its congener *Clavagella*, Lamarck, 1818 are similarly constructed. These funnel-shaped collars (see Fig. 7A₁), built of calcite, are the only preserved fragments of these bivalves, the aragonite-built remaining part of the tubes and the whole shell being dissolved (Bałuk and Radwański, 1984; Figs. 2 and 7A₂, A₃ herein; Dulai, 1996).

Similar life requirements are also inferred from the clusters of endobenthic bivalves *Panopea* (see Fig. 7C), preserved as sandy internal moulds of originally aragonitic shells. Their moulds, mass-occurring locally (e.g., at Romaniv, see Fig. 8; individually at Stratyn, see Fig. 7D), all stand vertically in life position, as do living bivalves stretching out their siphons, through a sandy layer, to a temporary Middle Miocene (Badenian) sediment/water interface.

Uniformitarian criteria may, in the Mykolaiv Sands, also be applied to the cirripede genus *Creusia* Leach, 1817, the present-day representatives of which live as obligate as endo-commensals of scleractinian corals in extremely shallow-marine habitats (see Boucot, 1990, pp. 15–18). Their calcitic shells, as those from Stratyn (Fig. 6B₁, B₂) we infer as derived from aragonite, scleractinian colonies, *via* surf action or otherwise hydrodynamically rather than by chemical filtering [The latter was not a case in the *Creusia* shells studied, as they are contained in a sand matrix (see Fig. 6B₁, B₂), instead of resting in a hollow left after a dissolved scleractinian colony]. There are bathymetric (shallowest to intertidal) and climatic (sub- to tropical) requirements in extant species of this genus.

This facies- or substrate-restricted biota may indicate either an *in situ* preservation to form an autochthonous community/assemblage (e.g., taxodiacean stumps in sands; *Diopatra* and *Panopea* from overlying beds, see below), or the fossils (fragmentary like *Stirpulina*, complete as *Creusia*) more commonly belong to allochthonous assemblages which dominate in the sections studied. Those, being preserved near the original life habitats, are classified as parautochthonous assemblages.

All allochthonous assemblages studied have variable content and diverse frequency. All include representatives of diverse ecological groups, ranging from endo- and epibenthic,

sessile and vagile, nekctic (sharks) to pelagic (driftwood, ?succinite). Apart from the plants and shark teeth, all invertebrate fossils contained are either represented by their complete shells/tests (such as echinoids with their spine canopy, starfish skeletons, the cirripede *Creusia*), or by disintegrated/disseminated parts/ossicles (such as isolated echinoid spines and plastrons, starfish ossicles, small scallop valves). Of the latter group, there also occur locally (at Khorosno), but quite common there, disseminated plates of the stalked cirripede genus *Scalpellum* Leach, 1817, unknown as yet from the Ukrainian part of the Fore-Carpathian Basin; the collected plates (see Fig. 6A₁, A₂) resemble *Scalpellum burdigalense* Des Moulins, 1875 (see Withers, 1953, fig. 95).

THE BURROWS

Diverse burrows are typical features of all sections studied. The most common are “classical” *Ophiomorpha nodosa* Lundgren, 1891, ascribed for over half a century (Weimer and Hoyt, 1964) to shrimps of the genus *Callinassa* Leach, 1814. Their present-day producer *C. major* Say, 1818, is nowadays classified to the genus *Callichurus* (see Goldring *et al.*, 2004). These burrows, either very friable, or more less firmly cemented, occur singly in most of the layers throughout the whole sequence (see Fig. 8), except in some thick-bedded ones (cross-bedded, or homogenous). In some horizons they are abundant, crowded together densely in vertical position (e.g., at Stratyn).

The less common burrows are these of the Ghost Crab *Ocypode*, usually associated with those of *Callichurus*, and frequent in some horizons, mostly at Stratyn from where they have been described (Radwański *et al.*, 2012).

Locally abundant, and mass-aggregated in residual lags, are burrows of echinoids *Echinocardium leopolitanum* (e.g., at Gleboviti, Yasnytska), which have also been studied separately (Radwański and Wysocka, 2001, pl. 8, figs. 1, 2).

There are large, individual multiple-funnel shaped burrows, 20–30 centimetres deep, which are ascribed to the activity of sea anemones (see Wysocka, 2002, p. 553, pl. 9, figs. 1, 2 and 4; Radwański *et al.*, 2012).

There are also undetermined pocket-shaped burrows comparable to these of present-day holothurians of *Thyone*-type (*cf.* Howard, 1968, fig. 2), and burrows which may be ascribed to the activity of polychaetes and bivalves other than those discussed above.

TYPICAL SECTIONS

In Opole Minor, several tens of exposures of the Mykolaiv Sands show the variability of sedimentary structures and biotic content. End members are shown on selected sections (Fig. 8), one of which (Gleboviti) has previously been studied systematically.

Romaniv, an abandoned local sand-pit (previously unreported), lies along a stream escarpment, exposing a tripartite section about 15 m thick. It starts with fine-grained, strongly deformed, and occasionally structureless sands, where

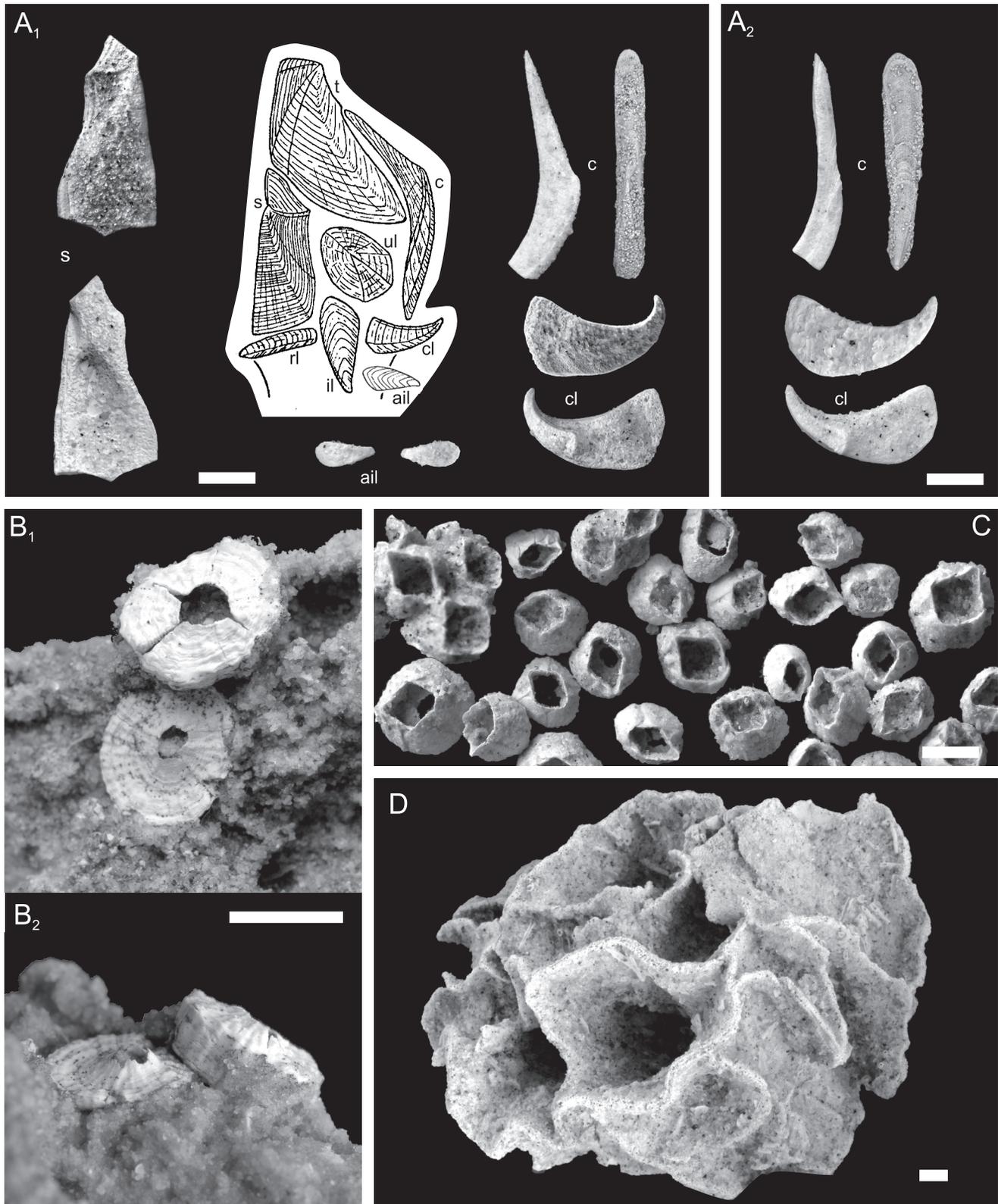


Fig. 6. Allochthonous assemblages of fossils at Khorosno and Stratyn

A – stalked cirripede *Scalpellum burdigalense* Des Moulins, 1875: **A₁** – restored array (right side) of plates armouring the capitulum, combined from des Moulins (1875, pl. 2) and Withers (1953, fig. 95), and isolated plates from Khorosno: s – left scutum (outer and inner views), c – carina (side and top views), cl – right carinolatus (outer and inner views), ail – additional infralatus (outer and inner views), t – tevgum, ul – upper latus, il – intramedian latus, rl – rostral latus; **A₂** – carina and right carinolatus of other specimens, isolated plates; **B₁**–**B₂** – two specimens of the cirripede *Creusia* sp., in top (**B₁**) and side (**B₂**) views, from Stratyn; **C** – isolated (substrate detached) crowns of the cirripede *Balanus* sp., from Khorosno; **D** – complete bryozoan colony of *Sertella* (?*Retepora*) type, from Khorosno; scale bar is 0.5 cm

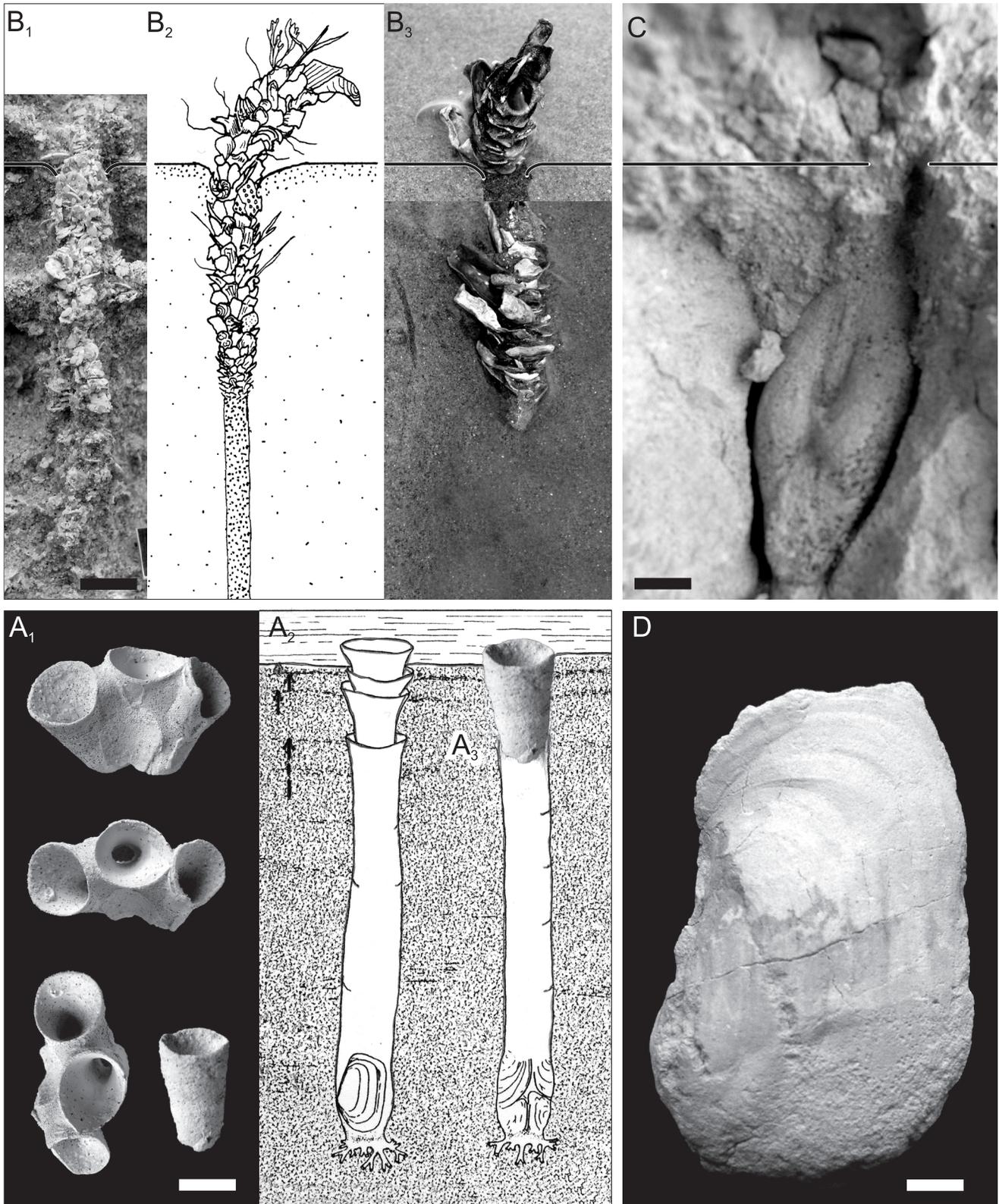


Fig. 7. Intertidal fossils of the Mykolaiv Sands and overlying limestones

A₁ – funnel-shaped collars (a group of three, and one isolated) of siphonal tubes of the bivalve *Stirpulina* from Gleboviti; A₂, A₃ – scheme of the shell structure in *Stirpulina bacillum* (Brocchi, 1814) from the Korytnica Basin in Poland (adapted from Bałuk and Radwański, 1984, fig. 2); in specimen from A₃ an isolated collar (A₁) is mounted, to show the whole shell construction; B₁ – tube of a polychaete of *Diopatra*-type from Khorosno; B₂ – scheme of tube of the present-day *Diopatra cuprea* (Bosc, 1803) from the Georgia coast, U.S.A. (adapted from Myers, 1970, fig. 1a); B₃ – similar tube construction from the present-day intertidal Gomso Bay, western coast of South Korea (photo by A. Wysocka, 2006); C – *Panopea* internal mould (steinkern) in life position of the bivalve at Romaniv, field photo; D – isolated specimen (internal mould) of *Panopea* from Stratyn; in Figure 7A₂–A₃, B₁–B₃ and C indicated is a temporary sediment/water interface; scale bar is 1 cm

small-scale south-inclined folds predominate. Anticlinal parts of these folds are steeper, than synclinal ones, and they are overlain by non-deformed deposits. In the upper part, a large-scale, low-angle cross-bedded set with abundant *Ophiomorpha* burrows is present. Above, there are planar cross-bedded biocalcarenes. The section is terminated by marly limestones, the lowermost layer of which has common *Panopea* preserved as sandy shell moulds; these stretch out with their gaping valves upwards, in life position, to represent an autochthonous community or “frozen behaviour” (*sensu* Boucot, 1990).

The biotic content of allochthonous assemblages, apart from the bryozoan detritus, is very scanty, containing the large foraminifer *Heterostegina* and the small echinoid *Echinocyamus*.

Stradch, an abandoned sand-pit, displays large channel-like infills and deformational sedimentary structures that recur several times in the section. The channel-like infills, in most cases, are structureless in their lower parts (but contain residual lags) and strongly deformed in their upper parts. Moreover, the largest ones are associated with deformations of the surrounding sand, ranging from small-scale convolute bedding to diapirs 2 metres high (see Wysocka, 2002, pl. 7, fig. 1) likely generated by overload of channel infills upon cohesive unstable sands. The 20 m thick sequence is directly overlain, with a sharp boundary, by the Ratyn Limestones.

Biotic content comprises only large boulders of silicified wood seemingly in residual lags of the channel-like infills.

The section is interpreted as representing a deeper offshore setting with shore-faced sand-masses repeatedly slumped due to gradient increases and/or a seismic triggering.

Sykhiv, a newly re-opened sand-pit (see Wysocka, 2002), displays a bipartite sequence more than 20 m thick (*cf.* Teisseyre, 1938, p. 127), the lower part of which is built of tabular cosets of planar bedding, with subordinate cross-bedding, all having been almost completely blurred by intense bioturbation. The upper part is a very large cross-stratified set, unfossiliferous, and directed towards the south-west (Fig. 4A). Sporadically, channel-like scours filled with structureless sands appear in the lower unit containing numerous echinoid burrows. The sequence is overlain by marly red-algal (lithothamnian) limestones.

The section is interpreted as a result of rapid deposition, either of an extremely large (10 metres high), cross-stratified sand bar (presumably of storm origin), or progradation of a delta slope, which developed upon a monotonous planar-bedded rhythmic series of interbedded tabular and cross-bedded sets.

Gleboviti, a partly abandoned sand-pit, where exploitation reached nearly to the Upper Cretaceous basement upon which the silicified stumps of taxodiacean conifers are rooted (Radwański and Wysocka, 2001; Wysocka, 2002). The section comprises a 12 m thick sequence built of fine-grained sand units with various depositional and biogenic structures. The lower part is dominated by tabular cross-stratified sets, the middle one by cross-sets strongly bioturbated by the echinoid *Echinocardium leopolitanum*. Above them, a large-scale tabular cross-stratified set occurs. The sequence is terminated by tabular cross-sets with single burrows *Ophiomorpha*, and overlain by sandy red-algal (lithothamnian) limestones.

The biotic content is dominated by the ubiquitous echinoid *Echinocardium leopolitanum* Radwański and Wysocka, 2001, locally mass-aggregated, and preserved either with spine canopies or as naked tests. Spine-bearing examples present in storm layers, are associated with the starfish *Astropecten forbesi* Heller, 1858, preserved as complete skeletons. Naked tests are contained in cross-sets, and are commonly imbricated. Other fossils are extremely rare, and include tube collars of the bi-valve *Stirpulina* and shark teeth (*Odontaspis*, *Isurus*).

The section is interpreted as a facies succession of facies that ranges from an inferred coastal swamp undergoing transgression, to a distal sublittoral and deeper offshore setting, within a sequence of the reduced thickness (*cf.* Fig. 8). The mass-occurrence of *Echinocardium leopolitanum* suggests its provenance (as for the co-associated *Stirpulina*) from nearby intertidal settings, as with present-day relatives (see Radwański and Wysocka, 2001, p. 307; and Higgins, 1974, pl. 7b).

Stratyn, an abandoned sand-pit, has its lower part covered by quarry dumps. The accessible part of the section, over 10 metres thick shows ubiquitous and diverse burrows, of which those of the Ghost Crab *Ocypode* have been studied separately (Radwański *et al.*, 2012), and is overlain by marly biocalcarenes. The lower part of the section is locally uncovered, to show homogeneous sand, with an estimated thickness of some 20–30 metres.

The scarce biota is represented by small invertebrates, of which the rarest, but facies indicative, are the cirripedes *Creusia* (the only examples in the Mykolaiv Sands). More frequent are poorly preserved inarticulate brachiopods *Crania* (? or *Craniscus*), the echinoids *Echinocyamus* and *Spatangus*, isolated ossicles of the starfish *Astropecten*, small scallops and/or oyster detritus, as well as scattered large foraminifers *Heterostegina*.

The section is interpreted (*cf.* Radwański *et al.*, 2012) as reflecting progradation, through shallow subtidal to intertidal. Extremely shallow depths are indicated both by the burrows' producer, the Ghost Crab *Ocypode*, as well as by the cirripedes and brachiopods of likely paraautochthonous nature. Their, remains in the limited depth of water, were deposited very near the living communities.

Khorosno, an intensely exploited large sand-pit (previously unreported) shows a section about 20 m thick which is composed of two parts. The lower, about 10 m thick, is built of fine-grained quartz sands, with significant admixture of calcareous mud and clay minerals, showing channel-like scours (Fig. 4C) cut into cosets of tabular and trough cross-stratified sands (Fig. 4B, C). The basal parts of the scour infills are structureless, whereas the top parts are characterized by traces of lamination and numerous fold and diapir deformations (Fig. 4F). The same pattern takes place repeatedly, and particular scours and/or cosets of deformed sandy layers are vertically stacked. The deformations show south wards inclination of overturned anticlines, dying out upwards. These strata are covered by slightly deformed laminated sands with some clay (illite and/or folidoide). All are incised by a very large channel-like infill, capped by planar-bedded shallower sands with ubiquitous *Ophiomorpha* burrows.

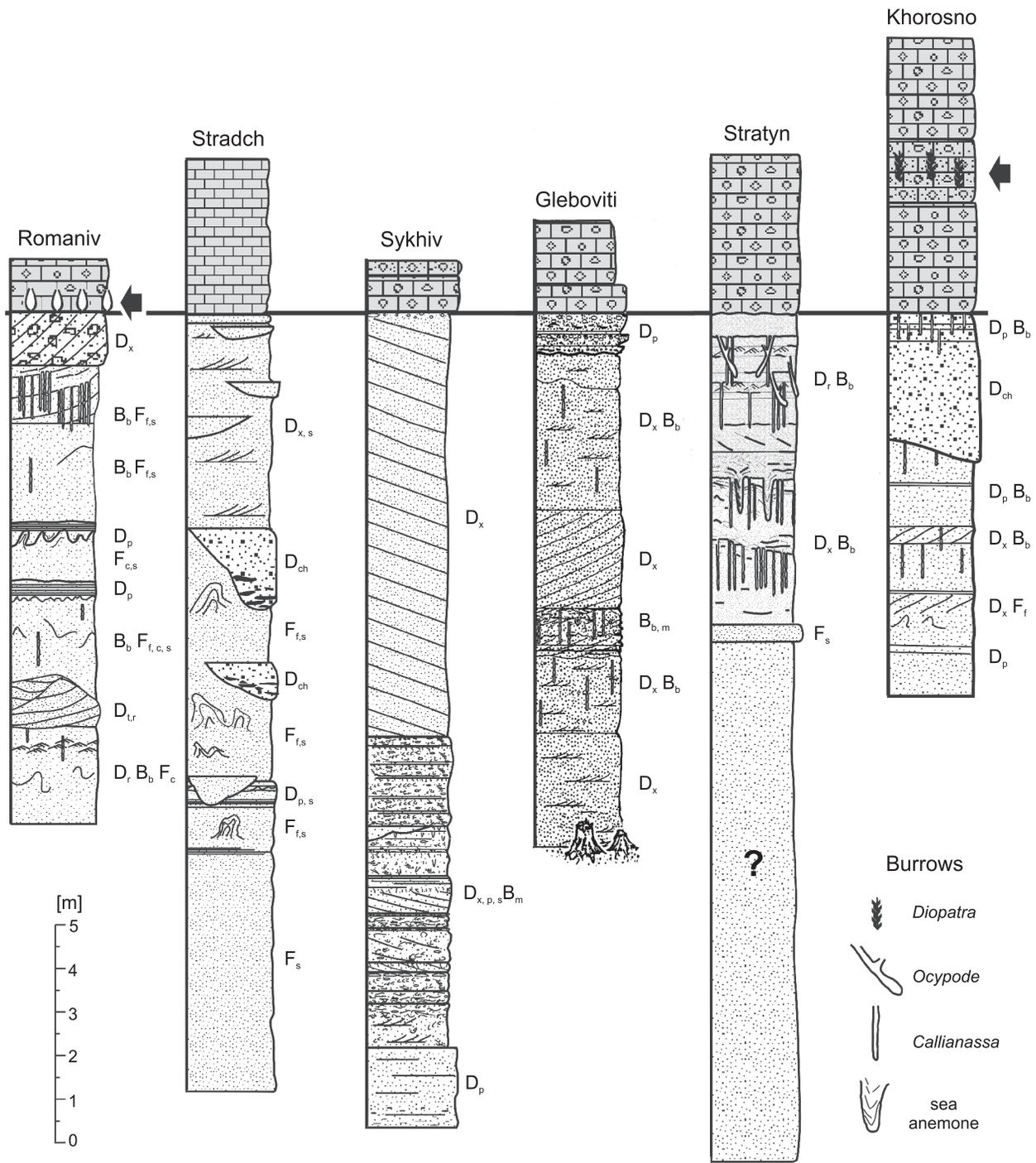


Fig. 8. Selected sections of the Mykolaiv Sands, to exemplify the diversity of sand bodies yielding variable sedimentary and biogenic structures, and their vertical succession

For other explanation see Table 1 and Figure 4; locations of intertidal biota in overlying limestones are arrowed

The biotic content is the most diverse among the sections studied. Contained mostly in cross-sets, it is composed of red-algal and fine bryozoan detritus, in which larger bryozoan colonies are common (Fig. 6D), associated with numerous large foraminifers (*Amphistegina*), empty crowns of the small acorn barnacle *Balanus* (Fig. 6C) and disseminated plates of the stalked barnacle *Scalpellum* (Fig. 6A₁, A₂), as well as

echinoderm clasts. The latter, taxonomically filtered (*sensu* Nebelsick, 1995), contain marginal ossicles of the starfish *Astropecten*, variably damaged tests of the echinoid *Hemipatagus ocellatus* (Defrance, 1827) and their fragments, the same as broken fragments of *Echinocardium leopoltanum* and of large *Clypeaster* sp. and *Conolampas* sp. The number of echinoid species totals twelve.

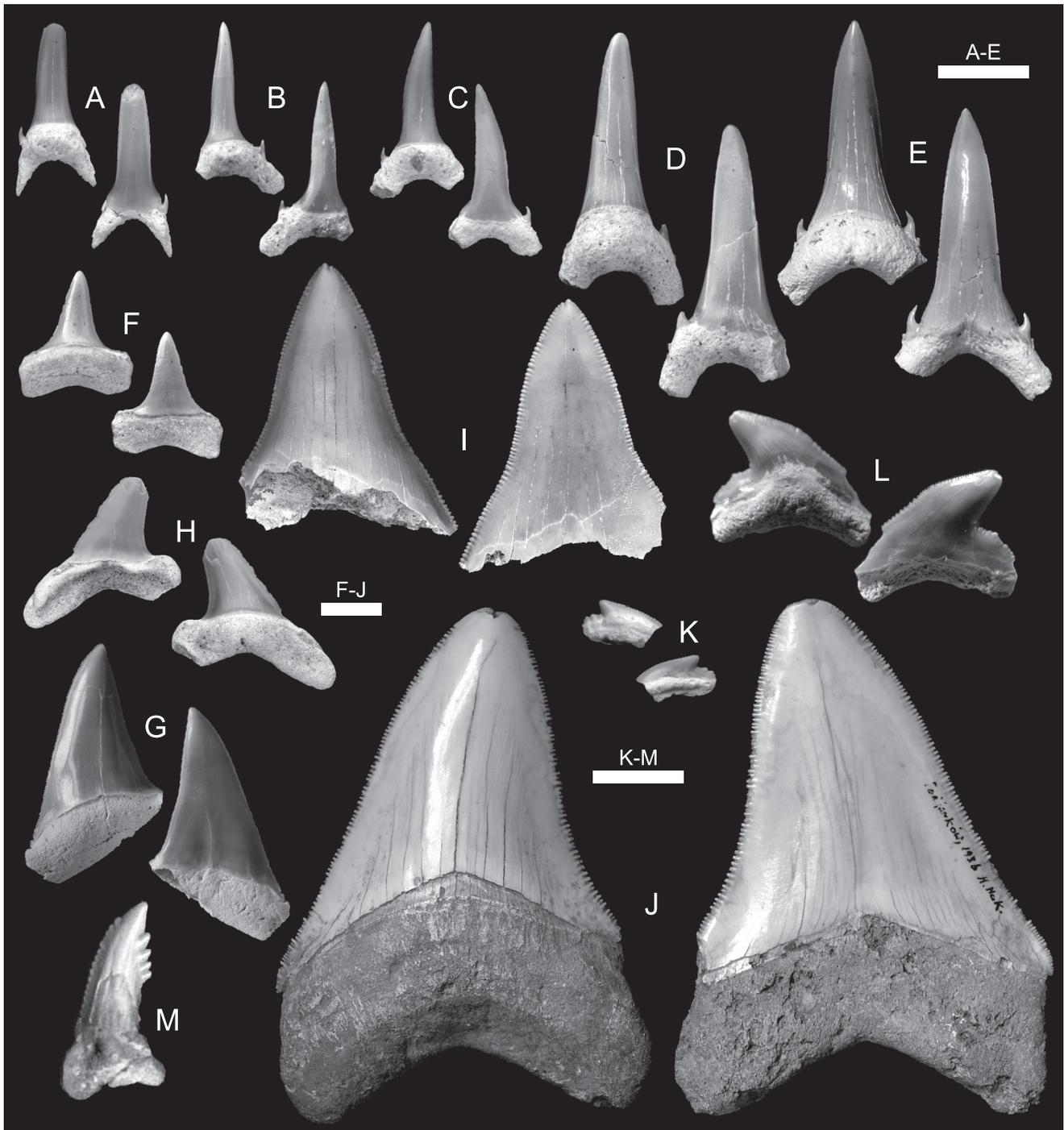


Fig. 9. Shark teeth from the Mykolaiv Sands; inner (lingual) and outer (labial) views

A–C – *Odontaspis acutissima* Agassiz, 1844, from Khorosno; D, E – *Odontaspis cuspidata* Agassiz, 1844, from Gleboviti; F, G – *Isurus hastalis* (Agassiz, 1843): F – lower posterior tooth (coll. M. Bieńkowska, 2006), G – upper anterior tooth, both from Gleboviti; H – *Isurus retroflexus* (Agassiz, 1843), lateral tooth from Khorosno; I, J – *Carcharodon megalodon* Agassiz, 1843: I – from Khorosno, J – from Pidiarkiv (coll. Makowski, 1936); K, L – *Galeocerdo aduncus* Agassiz, 1843: K – posterior tooth, L – lateral tooth, both from Khorosno; M – *Hemipristis serra* Agassiz, 1843: right lower lateral tooth in inner (lingual) view, from Berezhany (collection of O. Stalennyi, Ternopil); scale bar is 1 cm

The nektic elements are represented by the very common small, and rarely by large, scallops *Macrochlamis nodosiformis* (de Serres in Pusch, 1837), as well as by shark teeth (*Odontaspis*, *Galeocerdo*, *Megalodon*) and toothplates of rays (*Myliobatis*).

The section is interpreted as a result of accumulation, mostly by bottom currents, of diverse faunal remains which are otherwise under-represented or absent in other sections studied. The current-sorted remains form typical allochthonous assemblages. Their members show the diversity of the biotic communities and their life conditions over an extent of sea floor rang-

ing from eulittoral habitats (*Balanus*, *Scalpellum*), sublittoral photic zone of seagrass beds (bryozoans, *Amphistegina*, *Echinocyamus*, *?Clypeaster*, *?Conolampas*), to various offshore sandy bottoms (*Astropecten*, abundant but dwarfish echinoids *Psammechinus*), with common nektic elements (sharks and rays). Some of these forms (the cirripede *Scalpellum*, the ray *Myliobatis*) are new for the Ukrainian part of the Fore-Carpathian Basin.

A NOTE ON SHARKS

The Mykolaiv Sands contain common and diverse shark remains. Five genera have been recognized (see Fig. 9A–M): *Odontaspis*, *Isurus* (*Oxyrhina*), *Galeocerdo*, *Carcharodon*, and *Hemipristis*¹. Typically, their extant representatives are large, measuring up to 3–5 metres (*Carcharodon* even more) in length. This is apparently puzzling, if we consider the environmental conditions during deposition of the Mykolaiv Sands, suggesting a lack of space and of potential food for such large sharks. The three of the indicated genera, the Mako Shark (*Isurus*), the Tiger Shark (*Galeocerdo*), and the White Shark (*Carcharodon*), are known today for their extreme ferocity (see Budker, 1971, p. 119). Throughout the whole region of the Mykolaiv Sands, no satisfactory food source for them has been found. Of potential prey such as teleost fish and/or smaller marine mammals, no remains have as yet been found; dolphins (noted by Łomnicki, 1897 and Kudrin, 1957a, b) and porpoises (Kudrin and Tatarinov, 1965), are represented by single occurrences of bones/vertebrae.

The space was limited by the formation of diverse sand bodies, some rising to sea level. Such shallows/shoals could be favourable only for the smallest, the Sand Shark (*Odontaspis*), that today ventures into shallow offshore sand regions. This shark appears to be the commonest (see Fig. 9A–E) throughout the Mykolaiv Sands.

The rarest of the sharks recognized is the Snaggletooth Shark (*Hemipristis*), present-day representatives of which live in coastal waters of the Indian Ocean (Cappetta, 1987, p. 119); its teeth (see Fig. 9M) have not formerly been reported from the Ukrainian part of the Fore-Carpathian Basin.

The sharks in these deposits may simply have starved when prowling/wandering amidst the shoals and shallows of the Mykolaiv Sands, perhaps indicative of the open seaways through which they could spread from other Paratethyan basins, from where they are commonly known (see Radwański, 1965; Schultz, 1998, pl. 55), as in other shallow marine Miocene basins in Europe (see e.g., Leriche, 1957). This shark assemblage differs distinctly from those (which is composed of such genera as *Heptranchias*, *?Mitsukurina*, *Alopias*, and *Cetorhinus*) typical of the open-oceanic (Tethyan) realm pre-

vailing earlier in the Oligocene of the Carpathian Basin (see Bieńkowska-Wasiluk and Radwański, 2009).

REGIONAL INTERPRETATION

In general, the Mykolaiv Sands studied allow to understand their body as representing an extensive regional sandbody accretion prism which, in the Ukrainian part of the Fore-Carpathian Basin, carpeted the pre-Miocene topography at the margin of the East-European Platform, though not reaching the zone that was gradually downthrown south-westwards towards the Carpathian Foredeep. Such a tectonic setting is thus identical to that recognized in the Holy Cross Mountains (see Radwański, 1973, fig. 13) and Lublin Upland (see Wysocka, 2002, fig. 11) in the Polish part of the Fore-Carpathian Basin. This unit, though, covers a much larger extent and has a more complex anatomy, governed by both the pre-Miocene topography of the region and the dynamic conditions of the Middle Miocene (Badenian) transgression.

The sand supply is inferred to have been from Paleogene erosion of the East-European hinterland of Podolia and Volhynia (Radwański *et al.*, 2012). The mode of its delivery is as yet unknown: neither fluvial or aeolian transport, nor deltaic input has been recognized in the sequences studied. All facies studied (see Table 1) are typical of very shallow-marine, high-energy bottom conditions.

At the first stage of transgression, sand was swept into topographic depressions of Paleogene age, with an early suggestion (Teisseyre, 1938), of current deposition along the leesides of bottom hummocks of the Cretaceous basement, remaining plausible. An uneven bottom morphology, at this stage, controlled current directions (Wysocka, 2002) until the topography was smoothed by sedimentation to form an extensive offshore zone. As long as topography remained, slumping and liquefaction were locally important, to produce homogenized sand bodies up to 15 metres thick. Then, the sand bodies were influenced by storms agents (with scouring and residual lags), or by waves and currents, to produce sand bars of variable heights (up to 4, rarely to 10–15 metres). Amongst these the planar to small-scale cross-stratified sequences suggest meander processes, some reminiscent of tidal creeks (see Wysocka, 2002, figs. 10, 11). As there is no evidence of tidal action in the Fore-Carpathian Basin, such conditions are thought to have involved extreme offshore winds (a “pseudotidal effect”) or regional lowstands. The latter could have resulted from tectonic uplift of the shore and adjacent hinterland, or from compensation of subsidence by terrestrial increasing supply (significant evaporation is precluded, based on the faunal evidences).

Within this physical background, the biosedimentary structures of the Mykolaiv Sands are important. The best defined

¹ These classical genus names (see Budker, 1971; Cappetta, 1987) are used herein to be accessible for the readers less advanced in the widespread modern “jungle” of shark taxonomy

burrows, those produced by shrimps (*Callianassa vel Callichurus*) and crabs (*Ocypode*), yield environmental information consistent with the sedimentary data. These burrows indicate extremely shallow-marine high-energy habitats, under subtropical to tropical climatic conditions (see Goldring *et al.*, 2004; Radwański *et al.*, 2012). Those of the Ghost Crab *Ocypode* document local emergence (e.g., at Stratyn, see Radwański *et al.*, 2012).

Under these conditions, the ubiquitous sessile and vagile benthos flourished, with biodiversity greater than in the Polish part of the Fore-Carpathian Basin. In both parts, Polish and Ukrainian, the total marine assemblages, from various facies, indicate an influx of tropical/subtropical elements of the Indo-West Pacific Bioprovince (Bałuk and Radwański, 1977; Radwańska, 1992; Radwański *et al.*, 2006). Faunal elements new to the Ukrainian part of the Fore-Carpathian Basin include the cirripede *Creusia*, the burrowing crab *Ocypode*, and the shark *Hemipristis*. The biotic conditions illustrate well the global Langhian Climatic Optimum of the earliest Middle Miocene, prevailing during the early Badenian (see Harzhauser *et al.*, 2003, p. 336; Kroh, 2007).

Tropical/subtropical climatic conditions prevailed across the whole Fore-Carpathian Basin, regardless of its northernmost location among the network of Paratethyan basins. These conditions were thus evidently warmer than those suggested by Kroh (2007, p. 195), though a wider extent of the tropical zone in early Middle Miocene time was also considered by that author (Kroh, 2007, p. 169).

The variable bottom morphology in the studied part of the Fore-Carpathian Basin created a number of more or less specialized communities (some monospecific), which were intermittently destroyed in high-energy events, such as storms, strong waves and current scouring. Most of the faunal assemblages preserved were swept out of their life positions, and deposited at a shorter (parautochthonous assemblages) or greater (allochthonous assemblages) distances from them. Deeper erosion could locally produce residual lags of early cemented echinoid burrows (of *Echinocardium* at Gleboviti; see Radwański and Wysocka, 2001, p. 309 and pl. 8, figs. 1, 2). The rare autochthonous assemblages, apart from the taxodiacean stumps, preserved *in situ* in their life position, include the *Ocypode* burrows indicative of sub- to intertidal conditions. The latter suggest a diminishing water column at the final developmental stage of the Mykolaiv Sands.

Overlying the Mykolaiv Sands are (except for the local Ratyn Limestones) the lithothamnian limestones of the Mid-Lithothamnian Horizon, the regional significance of which remains unclear. Their variable structure (sandy or clay intercalations) and thickness (from several centimetres to several metres, locally up to 20 m; see Łomnicki, 1897; Teisseyre, 1938; Pazdro, 1953), as well as a total absence of higher-energy dynamic events, suggests a regional dynamic lull.

In the sections studied, the boundary between the Mykolaiv Sands and the Mid-Lithothamnian Horizon is put at the base of the first lithothamnian layer, continuous across each section ex-

posed. Nevertheless, this almost barren horizon includes as well as such nektic elements as valves of small scallops, distinctive benthic elements. Apart from local oyster detritus, these are the polychaete tubes of *Diopatra*-type at Khorosno, and a “frozen” bed of *Panopea* bivalves buried *in situ* in life position at Khorosno (see Fig. 8) and Vybranivka. All occur at the basal part of the Mid-Lithothamnian Horizon, to demonstrate continuity of extremely shallow marine environmental conditions typical of the higher parts of the Mykolaiv Sands. The common thin-bedded planar stratification on these lithothamnian layers are reminiscent, though, of lacustrine or lagoonal rather than shallow open-marine sequences. Nowak (1938), in this context, suggested that the regional precipitation of calcium carbonate, involving profuse growth of lithothamnian red-algae, was in fact of evaporitic nature, preceding the formation of the Gypsum Series. This lies beyond the scope of the present paper, but the Mid-Lithothamnian Horizon seemingly formed under the same dynamic conditions as the Mykolaiv Sands, and its variable thickness was controlled by the uneven bottom topography formed by the topmost part of this sandbody.

The presence of the tropical/subtropical Indo-West Pacific biotic elements shows that the accumulation of the Mykolaiv Sands took place during the Langhian Climatic Optimum in early Badenian time. Their accumulation thus evidently took place prior to the Badenian Salinity Crisis (13.8 Ma: formation of Gypsum Series), which involved a dramatic drop in sea level, controlled by the tectonic evolution (nappe formation and orogenesis) of the Carpathian Range (Peryt, 2006). A primary control by the glacial event Mi-3b involving astronomical cycles, as recently envisaged by de Leeuw *et al.* (2010), may also be taken into account. The resulting drop in temperature and deprivation of thermophilic biota was a harbinger of the “Ice-house phase” in climatic records of the younger Neogene (see de Leeuw *et al.*, 2010, p. 716 and fig. 3; cf. also Böhme, 2003, fig. 2). In consequence, the open-marine tropical/subtropical biota of the Indo-West Pacific provenance never returned to the Fore-Carpathian Basin. The biotic content of the Mykolaiv Sands, similar to that of the Medobory Biohermal Complex (see Radwański *et al.*, 2006), remains thereby a captivating document of the “Greenhouse phase” (de Leeuw *et al.*, 2010) of Neogene climate in Western Ukraine and the whole Fore-Carpathian Basin.

Acknowledgements. Cordial thanks are offered to the reviewers, Prof. Dr. A. Uchman (Jagiellonian University, Kraków) and Dr. K. Zágöršek (National Museum, Prague), as well as to Prof. Dr. T. Peryt (Polish Geological Institute – National Research Institute, Warszawa), whose constructive remarks have improved and enriched this paper. Cordially thanked is also Dr. M. Bieñkowska-Wasiluk for a kind donation of a shark tooth (see Fig. 9F). Fieldwork was partly supported by the Ministry of Science and Higher Education (Grant N 307 113635, of 2008-2011) and by the University of Warsaw (BSt 1536/2).

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