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VERSITA

Miocene burrows of the Ghost Crab *Ocypode* and their environmental significance (Mykolaiv Sands, Fore-Carpathian Basin, Ukraine)

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ABSTRACT:

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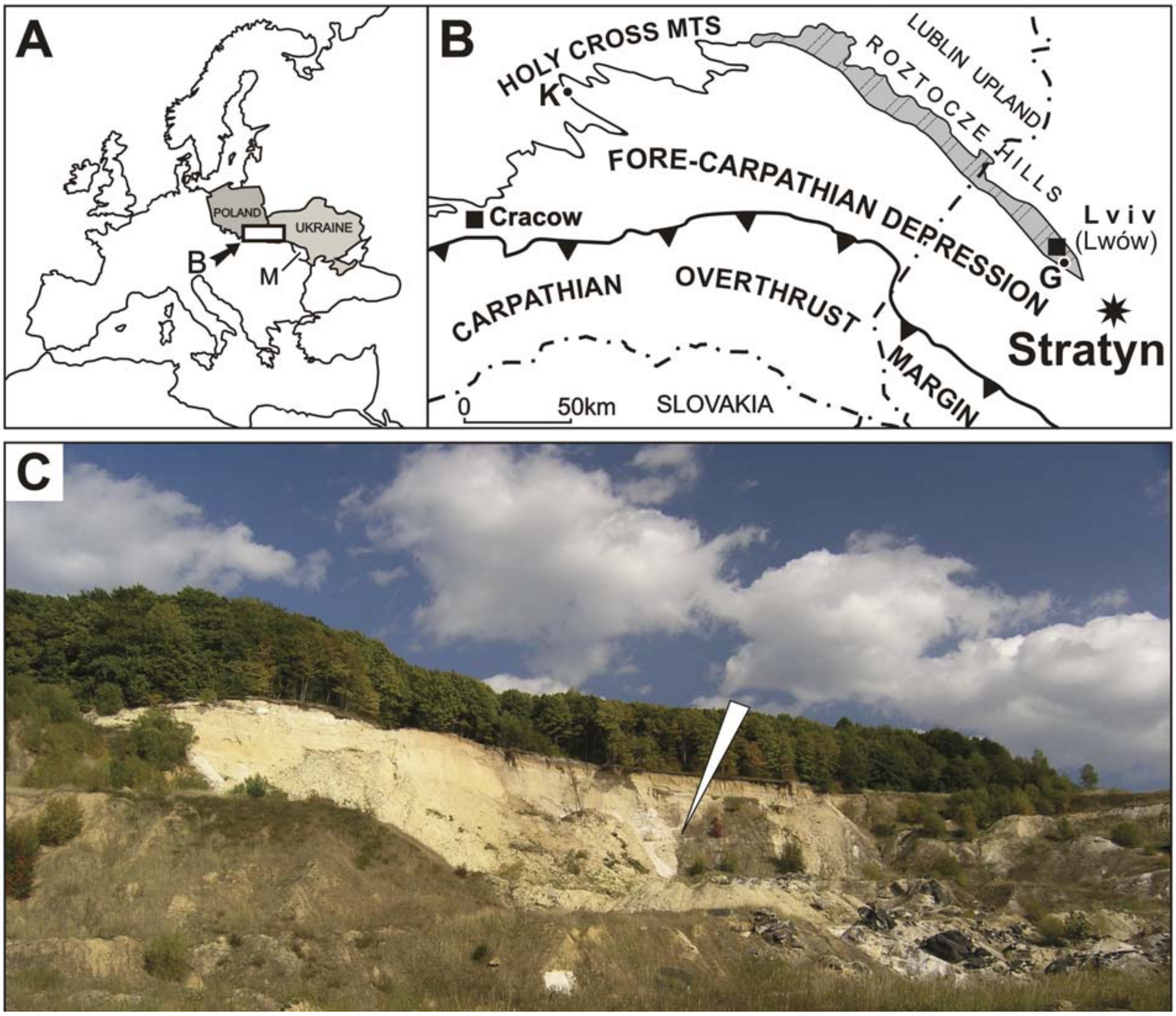
The huge lithosome of the Middle Miocene (Early Badenian) Mykolaiv Sands, developed at the external margin of the Fore-Carpathian Basin in western Ukraine, is recognized to represent a shallowing-up sequence. Special attention is paid to burrows of the Ghost Crab *Ocypode* which are pantropical in present-day littoral habitats. In the Stratyn section, burrows of this type become a crucial tool in the interpretation of basin bathymetry, which starts from distal offshore depths, through the foreshore, to the backshore where the *Ocypode* burrows record a temporary break in sedimentation. Lithification of the sand layers and the *Ocypode* burrows subsequently progressed in beachrock mode. The Stratyn section demonstrates that the development of submerged shoals and/or emergent parts, throughout the huge mass of the Mykolaiv Sands, is probably responsible for their great variation in thickness in western Ukraine, which has long proved difficult to explain.

Key words: Burrows; Ghost Crab *Ocypode*; Palaeoenvironment; Sedimentology; Middle Miocene; Badenian; Paratethys; Ukraine.

INTRODUCTION

The outer, marginal parts of the Fore-Carpathian Basin contain a wide range of diverse lithofacies, reflecting the varied basin topography and character of the source areas of the terrigenous material in the hinterland of Podolia and Volhynia. The Mykolaiv Sands (piaski mikołajowskie, in Polish), with a wide areal extent in Ukraine and in the Polish Roztocze Hills (see Wysocka 1999, 2002; Radwański and Wysocka 2001), belong to one of these lithofacies (see Text-figs 1–2). They are well exposed along a continuous zone, or in numerous outliers, in several sandpits or larger quarries.

The Mykolaiv Sands are commonly devoid of any biota, but are characterized by an ubiquity of sedimentary structures, both physical (see Wysocka 1999, 2002) and biogenic. The latter are represented predominantly by burrows of diverse plants and/or animals, all of which remain as yet unstudied. The aim of the present paper is to discuss the environmental significance of peculiar large burrows, of a type produced today by the Ghost Crab, *Ocypode*. Their occurrence was first noted by Wysocka *et al.* (2010).



Text-fig. 1. **A** – General setting of the study region (**B**) in Europe (M – the Republic of Moldova); **B** – Lviv region in western Ukraine, containing the Middle Miocene (Badenian) sequence exposed at Stratyn (arrowed), and its location at the external margin of the Fore-Carpathian Depression; indicated are the cited localities in Ukraine (G – Gleboviti near Lviv) and Poland (K – Korytnica); **C** – Panoramic view of the quarried sand-pit at Stratyn (arrowed, see Text-fig. 3), September 2009

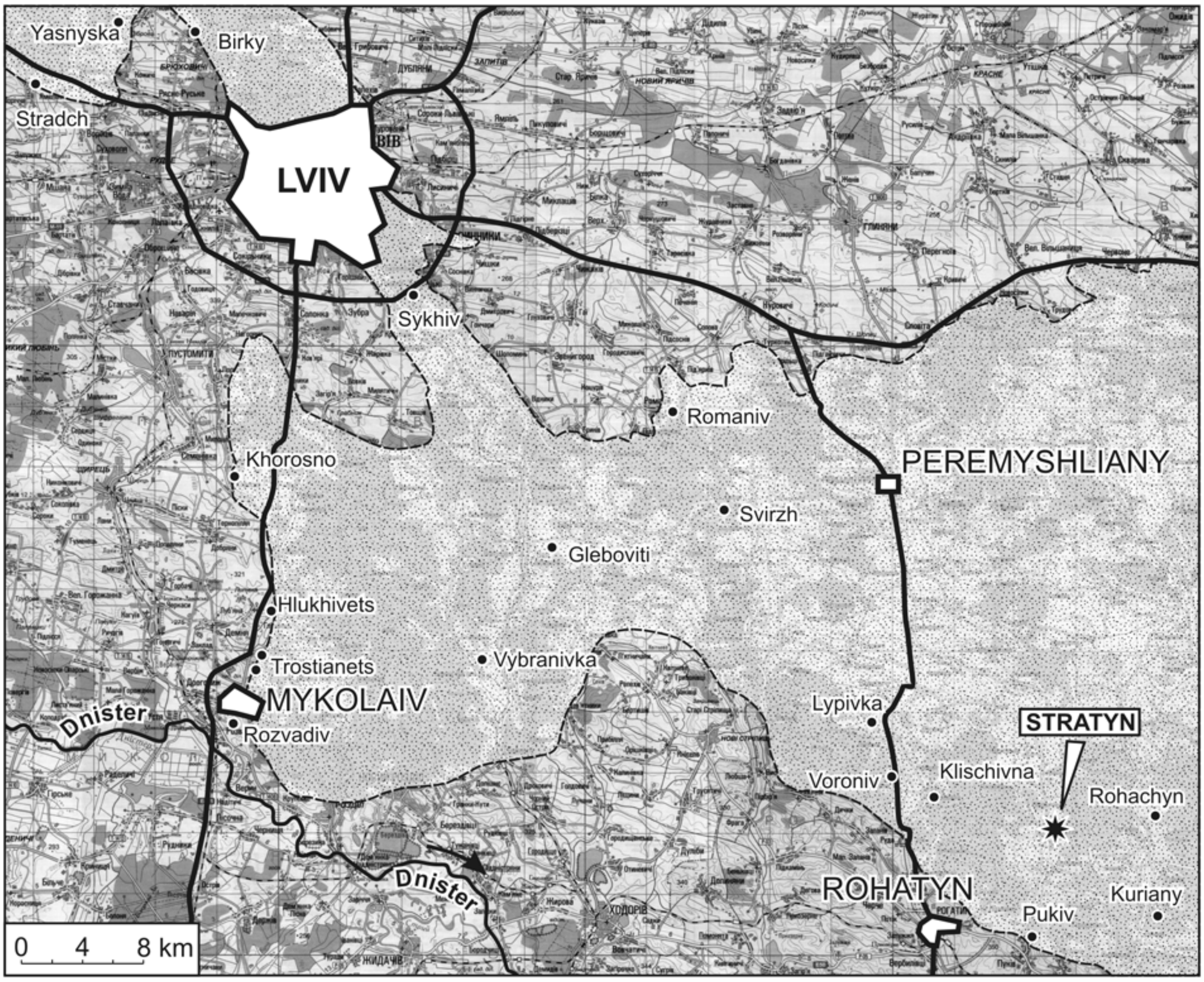
GEOLOGICAL SETTING

The Mykolaiv Sands form part of the widespread sand-mass of the Middle Miocene (Badenian) transgressive sequence overlying Upper Cretaceous marls in the Lviv region in western Ukraine (see Wysocka *et al.* 2012). This huge lithosome is composed of nearly pure quartz sands, with subordinate glauconite and, more commonly, biocalcarenites. Its thickness ranges from almost a hundred metres to nil, dependant on the pre-Miocene topography (see Teisseyre 1938; Pazdro 1953; Wysocka 2002). The Mykolaiv Sands are capped by marly biocalcarenites with red-algal (lithothamnian) detritus (the Mid-Lithothamnian Horizon *sensu* Łomnicki 1897).

The Mykolaiv Sands underwent several diagenetic events, primarily the dissolution of aragonite, and pressure solution. Due to the latter, the calcitic fossils are more or less heavily armoured with sand grains (see Radwański and Wysocka 2001). Consequently, the body-fossils are represented mostly by the skeletal parts of echinoderms, either echinoids or asteroids (see Szörényi 1953; Kudrin 1957; Radwański and Wysocka 2001; Wysocka *et al.* 2012).

STRATIGRAPHIC AGE

The faunal content of the Mykolaiv Sands is indicative of open-marine conditions, with oceanic in-



Text-fig. 2. Topographic map of the Lviv region in Ukraine (see Text-fig. 1), to show the extent of the Middle Miocene (Badenian) sequence of the Mykolaiv Sands (shaded) and their representative exposures

fluences from the Indo-Pacific bioprovince (see Wysocka 2002; Radwański *et al.* 2006). In the Middle Miocene of the Fore-Carpathian Basin such conditions happened only once. Consequently, the Mykolaiv Sands can be dated as Badenian (see Harzhauser *et al.* 2003; Kroh 2005), and are thus coeval with the classic Korytnica sequence of southern Poland (see Bałuk and Radwański 1977; Radwański *et al.* 2006), as well as with part of the Badenian stratotype succession at the Baden-Sooss section in the Vienna Basin (see Rögl *et al.* 2008). The correlation of the Mykolaiv Sands with the foraminiferal (lagenid) ecozonation and the calcareous nannoplankton zonation in the Polish part of the Fore-Carpathian Depression (see Rögl and Brandstätter 1993, pp. 142–144), is uncertain.

The presence of tropical/subtropical Indo-Pacific biotic elements, widely discussed earlier (Radwański 1974, 1975), allows the Mykolaiv Sands to be assigned to the Langhian Climatic Optimum of the earliest Middle Miocene (Early Badenian; see Harzhauser *et al.* 2003, p. 336). This event evidently preceded the Badenian Crisis (which involved a fall in sea level), after which the connections to the Indo-Pacific area have never been established (see Radwański *et al.* 2006, p. 99; Wysocka *et al*. 2012).

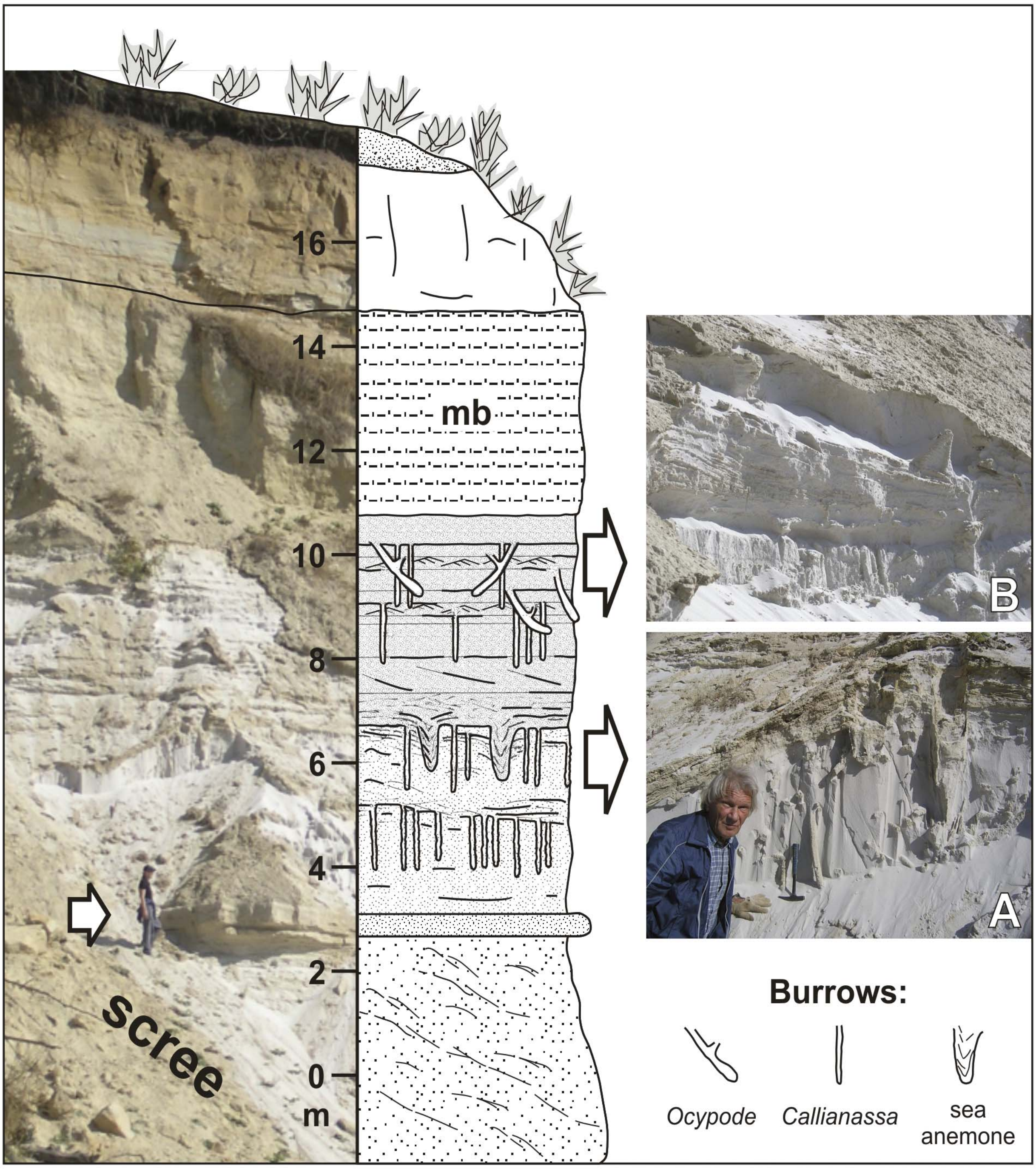
THE STUDIED SECTION

The studied section is an abandoned sand-pit, located at the village of Stratyn, some 40 km SE of Lviv (see Text-figs 1–2). Nowadays, only an upper part of the succession (c. 10 m thick, see Text-fig. 3) is exposed; with the exception of few small places, its lower part is covered by quarry dumps. The sandy sequence is covered by marly biocalcarenites (*mb* in Text-fig. 3). The Miocene succession is covered by 4 m thick Pleistocene loess.

The exposed part of the sandy sequence starts with a calcite-cemented, massive, c. 50 cm thick sandstone layer (Text-fig. 3). It is overlain by an over 7 m thick bedset of horizontally and ripple-cross bedded sands. Within this series, the two distinctive lithofacies are distinguished, described below in stratigraphic order.

The lower lithofacies

The lower lithofacies (see A in Text-fig. 3) is represented by poorly stratified sands, with abundant closely-spaced, vertical, almost straight burrows *Ophiomorpha* up to 80–90 cm long, similar to those illustrated by Frey and Mayou (1973, fig. 3) from the coast of Georgia, U.S.A.



Text-fig. 3. The studied Middle Miocene (Badenian) sandy sequence exposed at Stratyn; the densely burrowed parts (arrowed in field photos as **A** and **B** are shown in close-up view in Text-fig. 6A and 6B); mb – marly biocalcarenites overlying the sands; the burrows are not to scale, having been slightly exaggerated

Since the studies of Weimer and Hoyt (1964) such burrows are known to be produced today by shrimps belonging to the genus *Callianassa*, Leach, 1814. However, body remains of *Callianassa* associated with these burrows have only rarely been reported in the fossil record (e.g. Waage 1968, fig. 8C; Radwański and Wysocka 2004, p. 390 and pl. 9, figs 1–2).

The *Callianassa* burrows are very poorly cemented and always devoid of their apertural parts (cf. Weimer and Hoyt 1964, pl. 123, fig. 4).

Associated are shallower, funnel-shaped burrows, identical to those documented previously (Wysocka 2002, pl. 9, figs 1–2 and 4) from the localities Birky (Borki) near Lviv, and Gleboviti (see Text-fig. 2). Since the studies by Shinn (1968) on the present-day coasts of Florida and the Bahamas, such burrows are known to be produced by various sea anemones.

The upper lithofacies

The upper lithofacies is characterized (see B in Text-fig. 3) by more finely stratified sands, quite often rippled, with rarer burrows *Ophiomorpha*, which decrease in numbers upwards. In the upper part, all sedimentary structures are transected by large, broadly Y-shaped burrows, over 0.5 m long and 7–8 cm in diameter, and circular in cross-section, identical to those produced on present-day shores by crabs belonging to the genus *Ocypode*.

The *Ocypode* burrows are preserved almost completely, having been more or less cemented together with the host rock.

THE PRESENT-DAY *OCYPODE*

The animal

The present-day crabs of the genus *Ocypode* Weber, 1795 are pantropical (cf. Text-fig. 4A–E), with one species ranging as far as the southern Mediterranean (see Strachan *et al.* 1999). They inhabit the whole shorezone, from the shallowest subtidal (foreshore) up to the base of coastal dunes in the proximal supratidal (backshore). In some regions, they appear in dense, usually monospecific colonies, indicative of their well advanced territorialism (Warner 1977, pp. 116–118; see also Radwański *et al.* 2009, p. 466).

These crabs have long attracted attention due to their mode of life, sound, and locomotion (see, e.g., Cott 1929; Milne and Milne 1946; Fellows 1973; Vannini 1980). Generally nocturnal, when running rapidly sideways along the beach (on straightened legs: see Cott 1929, fig. 1; Glaessner 1969, fig. 338/3), they flee at the sight as if being 'true' ghosts (hence, their vernacular name). One of the earliest observers, Bosc (1802) noted (see also Milne and Milne 1946, pp. 362–363; Frey and Mayou 1971, p. 58) chasing them on horseback (!). They may be quite noisy due to the stridulating sound emitted by the males (see Alcock 1892; Cott 1929) to signalize their presence in the burrow.

Ocypode is also very attractive food, and not only for man. On the coast of Somalia, a troop of yellow baboons was observed (Messeri 1978, see also Vannini 1980) trying to catch them on the beach, or to extract them from their burrows (using cuttlebones as digging tools!).

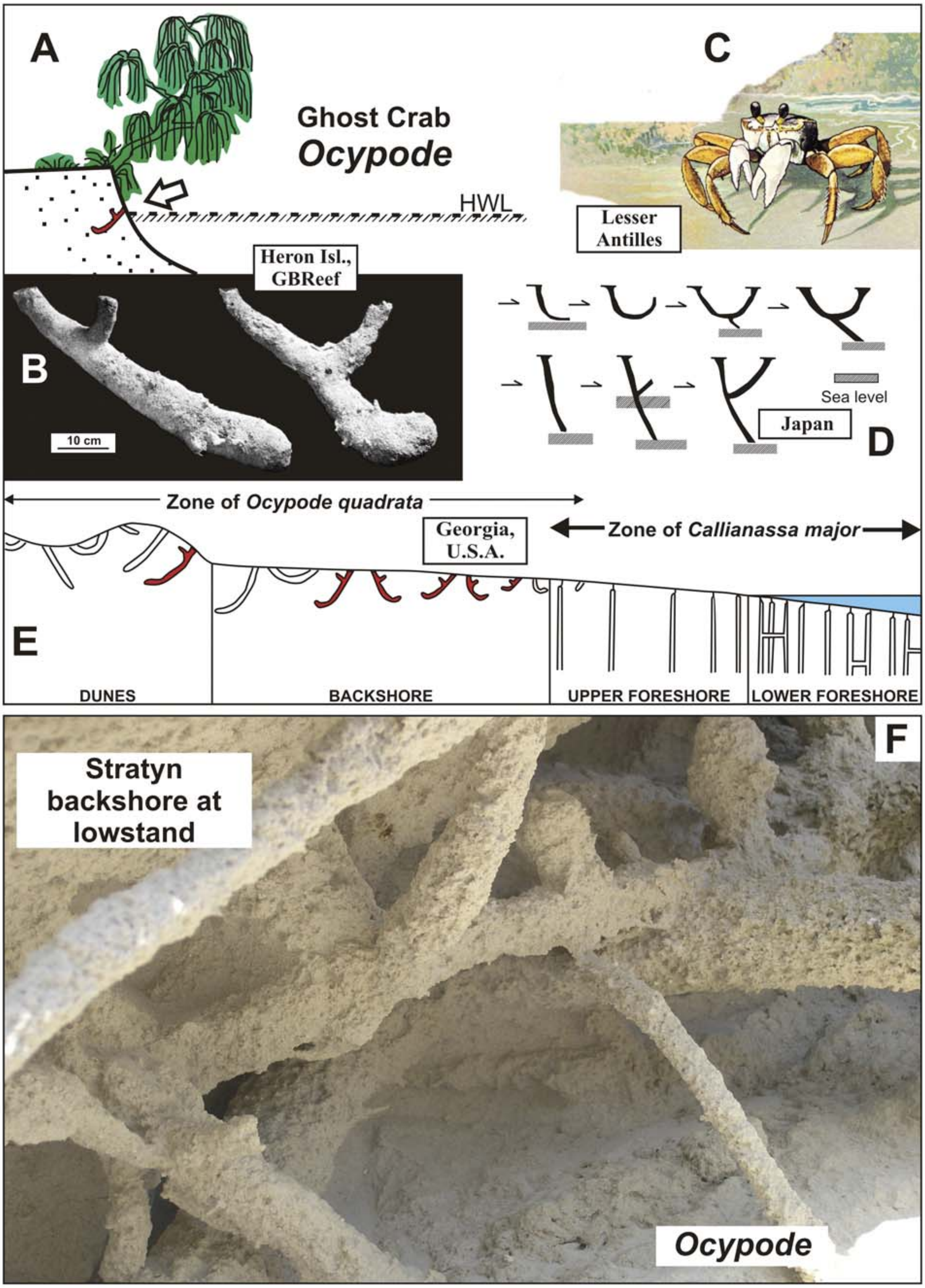
The burrows

The best documented data on the Ghost Crab *Ocypode*, including the morphology of their burrows, are from the shorezones of Taiwan (Hayasaka 1935; Takahasi 1935), China (Chan *et al.* 2006), Japan (Utashiro and Horii 1965; Seike and Nara 2007, 2008), Aldabra Atoll (Farrow 1971), Georgia, U.S.A. (Frey and Mayou 1971), Seychelles (Braithwaite and Talbot 1972), Texas, USA (Hill and Hunter 1973), Kiribati (Fellows 1973), North Carolina, USA (Allen and Curran 1974), Heron Island, Great Barrier Reef in Australia (Förster and Barthel 1978), Somalia (Messeri 1978; Vannini 1980) and India (Chakrabarti 1981; Patel and Desai 2009, p. 237 and fig. 5b).

The broad morphological variability of *Ocypode* burrows (see, e.g., Hayasaka 1935, fig. 2; Utashiro and Horii 1965, fig. 4 and pls 3, 4; Frey and Mayou 1971, fig. 3 and pls 2, 3; Vannini 1980, figs 4, 5; Chan *et al.* 2006; Seike and Nara 2007, fig. 3 and 2008, fig. 4) reflects the variability of their digging behaviour, their ontogeny, and the sexual dimorphism of the adults (see also Hughes 1973). All burrows are unlined, dug in loose sands. Their shape varies in particular shore zones, with the most characteristic being obtuse, Y-like forms, produced exclusively in the backshore up to the seaward base of the coastal dunes (see Frey and Mayou 1971, fig. 3; Braithwaite and Talbot 1972, figs 1–2; Förster and Barthel 1978, figs 2a and 3; Seike and Nara 2008, fig. 4G; cf. also Text-fig. 4 herein). Such forms are represented in the Mykolaiv Sands (see Text-figs 4F and 5A–B).

THE ANCIENT *OCYPODE* AND THEIR BURROWS

The genus has been commonly recorded from the Pleistocene to Recent (see Glaessner 1969, p. *R*530).


A
Ghost Crab
Ocypode
HWL
Heron Isl., GBReef
B
10 cm
C
Lesser Antilles
Sea level
Japan
D
Zone of Ocypode quadrata
Georgia, U.S.A.
Zone of Callianassa major
E
DUNES
BACKSHORE
UPPER FORESHORE
LOWER FORESHORE
F
Stratyn backshore at lowstand
Ocypode

Its first Miocene body-fossil (dorsal carapace) was reported from Patagonia, Argentina (Casadio *et al.* 2005). In Europe, its body fossils remain unknown.

The fossil *Ocypode* burrows were first recorded from the Miocene of Taiwan (Hayasaka 1935), with subsequent reports from the Pleistocene of the United States (Frey and Mayou 1971; Frey *et al.* 1984) and Japan (Seike and Nara 2007). From the Miocene of Europe they were first described by Radwański (1977a, b; see also Gutowski 1984) from the Korytnica Bay on the southern slopes of the Holy Cross Mountains, from the northernmost margin of the Fore-Carpathian Basin in Poland (see Text-fig. 1B). They were also noted from the Lower Pliocene (Zanclean) of Attica in Greece (Dermitzakis *et al*. 2009, fig. 3 and p. 15).The scarcity of fossil *Ocypode* burrows is caused primarily, as assumed by Frey and Mayou (1971, p. 58), by the low preservation potential of the loose sand in which the Ghost Crabs burrow in present-day habitats.

THE PROBLEM OF *PSILONICHNUS* FÜRSICH, 1981

When studying ichnofossils from the Kimmeridgian of Portugal, Fürsich (1981, p. 157) assigned Y-shaped burrows to a new, monospecific ichnogenus, *Psilonichnus*. He considered that the burrows were comparable to those made by present-day burrowing crabs, including the genus *Ocypode*, albeit he was aware that no such crabs had been evolved by that time. Unfortunately, his illustrated specimens (Fürsich 1981, pl. 1, figs 1–2) do not resemble any of the known *Ocypode* burrows. Indeed, they represent rather those of the Mud Shrimp *Upogebia* Leach, 1814 (see, e.g., Asgaard *et al.* 1997; Pervesler and Uchman 2009). The latter attribution was not excluded by Fürsich himself (1981), and was also suggested by Frey *et al.* (1984, p. 345). Consequently, it became evident that the ichnogenus *Psilonichnus* should be regarded as a *nomen dubium*. Frey *et al.* (1984, p. 344) have revised and emended the diagnosis of *Psilonichnus*, to make it compatible with the morphology of burrows of the burrowing crabs, particularly those of *Ocypode*. Moreover, they established a new ichnospecies, *Psilonichnus upsilon*, into the synonymy of which Frey *et al.* (1984, p. 345) included almost all of the fossil burrows ascribed formerly to *Ocypode*, particularly those illustrated by Frey and Mayou (1971) and Radwański (1977a, b). The type specimens (syntypes) of *Psilonichnus upsilon* come from the Pleistocene of San Salvador Island in the Bahamas.

The original diagnosis of *Psilonichnus upsilon* is as follows (Frey *et al.* (1984, p. 345): "Psilonichnians consisting typically of gently inclined, sparsely branched to unbranched, J- or Y-shaped burrows; inclined shafts straight to slightly arcuate; branches slightly to markedly curved, not horizontal". Effectively, this diagnosis selects exclusively and unites the J- and Y-shaped burrows into one ichnospecies, albeit at present-day locations such burrows differ in distribution (see above, cf. Text-fig. 4E). In the studied section only Y-shaped burrows occur.

Humphreys and Balson (1988) described burrows of the ichnogenus *Psilonichnus* from the Upper Pliocene of eastern England, and referred them to yet other crustaceans, possibly thalassinidean shrimps. Nara and Kotake (1997), as well as Seike and Nara (2007, p. 462), treated the ichnogenus *Psilonichnus* as probable upogebiid burrows (see other references in Pervesler and Uchman 2009).

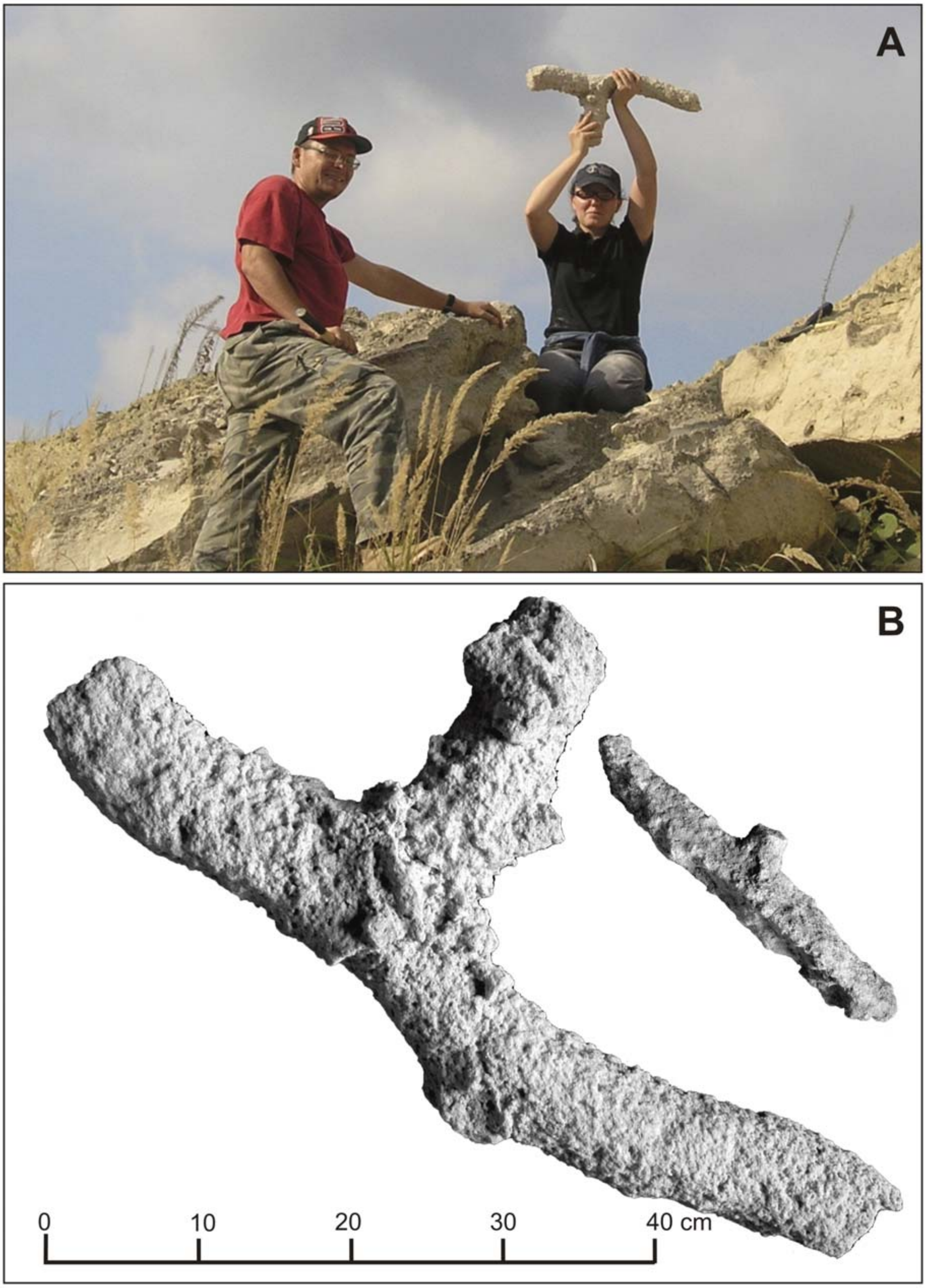
Under such circumstances, for further clarity and to avoid vagueness and/or confusion in the environmental analysis and ichnotaxonomy, the present authors choose to apply a neontological nomenclature for the burrows studied.

INTERPRETATION OF FACIES

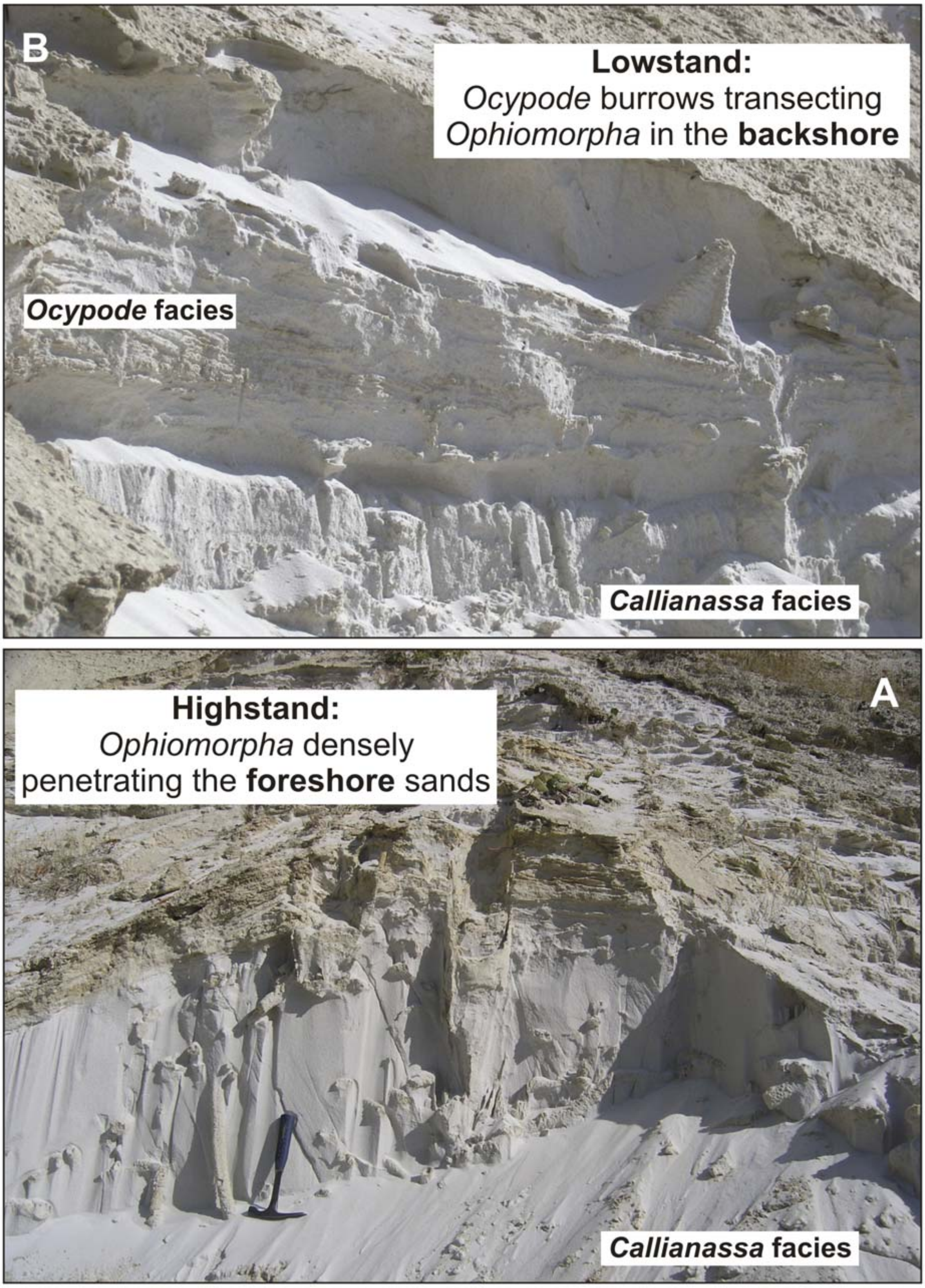
The Mykolaiv Sands, as exposed at Stratyn, represents a shallowing-up sequence. The basal, unexposed part of the succession indicates (Wysocka 1999, 2002) reworking of former deltas and/or other coastal deposits at the transgressive rise, through to the storm deposits and/or large-scale local slumping, all of which point to a more or less distal offshore (see Wysocka 2002, fig. 10).

The appearance of the *Callianassa* facies (see Text-figs 3–4) evidences the shallowing of the depositional setting of the Mykolaiv Sands to the limits of the foreshore zone. The scouring of the apertural parts of the burrows shows that this zone was still submerged and acted upon by hydrodynamic agents; a temporary highstand is therefore postulated (Text-fig. 6A).

Text-fig. 4. **A**–**E** – Present-day pantropical distribution of the Ghost crab *Ocypode* and their burrows: **A**, **B** – Heron Island, Great Barrier Reef, Australia (adapted from Förster and Barthel 1978, figs 2a and 3), to show location above the high water level (*HWL*); **C** – Ghost Crab with shore landscape of the Lesser Antilles as background (taken from a postage-stamp of the Grenadines of St. Vincent); **D** – Burrow diversity on a Japanese coast, in relation to sea level (adapted from Utashiro and Horii 1965, fig. 4); **E** – Zonation of burrows in barrier island beaches of Georgia, U.S.A. (adapted from Frey and Mayou 1973, fig. 3); **F** – Maze of burrows, interpreted as having been produced in a backshore zone of the studied Middle Miocene (Badenian) sequence at Stratyn in Ukraine



Text-fig. 5. **A** – Field photo, to show excavation of the largest *Ocypode* burrow at Stratyn, September 2009; **B** – The largest, almost complete, burrow of *Ocypode* associated with a minor one, from Stratyn



Text-fig. 6. Interpretation of the densely burrowed parts (A and B, see Text-fig. 3) in the sandy sequence exposed at Stratyn

A further shallowing is suggested by the observed burrow succession, which follows in stratigraphical order, the lateral sequence as observed in the Georgian coast (Frey and Mayou 1973, fig. 3; adopted herein in Text-fig. 4E). In the studied series, the *Ocypode* burrows transect those of *Callianassa*, The latter represent a former foreshore zone; those of *Ocypode* typify the uppermost foreshore zone and the whole backshore zone up to coastal dunes (Text-fig. 6B). Small, abundant, polydirectional ripples resulted from the activity of various coastal currents on vast tidal or pseudotidal flats. The compact sand layer, at the top of the succession, may correspond to a beachrock lithology such as has been recorded from the topmost parts of some shallowing-up Neogene sequences (see Radwański and Wysocka 2004; Radwańska and Radwański 2008).

As noted above, the *Ocypode* burrows are heavily cemented (see Text-figs 4F and 5A–B) and they arise from similarly compact sandstone layers (see Text-fig. 5A), which contrast with the surrounding loose sand (see Text-fig. 4F). A beachrock mode of cementation of burrows can thus be assumed.

A case of *Ocypode* burrows transecting shrimp (upogebiid) burrows at the top of a shallowing-up sequence, indicating a temporary break in sedimentation, has recently been illustrated from the Lower Pliocene (Zanclean) Rafina section in Greece (Radwańska and Radwański 2008, fig. 3; Dermitzakis *et al*. 2009, fig. 3).

The marly biocalcarenites overlying the burrow-bearing series (*mb* in Text-fig. 3), are devoid of depositional or biogenic structures. They are interpreted to have been deposited as a new highstand systems tract. This led to a deeper offshore environment, similar to and most probably coeval with that recognized in the Gleboviti section (see Text-fig. 2; and Radwański and Wysocka 2001, fig. 3 and p. 301). The observed environmental succession parallels the succession known from the Vienna Basin, where the 'Leithakalk' facies develops upon submerged rocky shoals (see Rögl *et al.* 2008, p. 368).

FINAL REMARKS

The succession of the Mykolaiv Sands at Stratyn demonstrates the high environmental sensitivity of the burrow assemblages. The neontological studies of the key burrows (e.g. Weimer and Hoyt 1964; Shinn 1968; Frey and Mayou 1973; Asgaard *et al.* 1997) clearly show that these burrows may be more precise indicators of bathymetry than any of the physical structures. The present-day lateral zonation of burrow types, cited herein, is clearly reflected by their vertical succession in the Mykolaiv Sands.

Consequently, the Stratyn section evidences a gradual shallowing of the basin, from distal offshore, through foreshore, to the backshore where the *Ocypode* burrows record a temporary break in sedimentation, caused most probably by emersion. The taphonomic and diagenetic features of the *Ocypode* burrows suggest the formation of beachrock, which indicates the appearance of emerging shoals upon the top of the Mykolaiv sand-mass. Although supralittoral forms (e.g. dunes, cf. Text-fig. 4E) are absent there, the non-deposition and/or removal of sands (?winnowing, coastal erosion) could have been responsible for the reduced thickness of the succession. This would provide a plausible explanation for the variable thickness of the Mykolaiv Sands recorded throughout the area of their occurrence (see Teisseyre 1938; Pazdro 1953; Wysocka 2002). A similar environmental interpretation, based on the *Ocypode* burrows, has recently been inferred for the Late Miocene lacustrine-deltaic sequence of the eastern Vienna Basin in Slovakia (Starek *et al*. 2010; Šimo *et al*. 2011, p. 48).

The Stratyn succession is also significant for the fossil burrows of *Ocypode* themselves. Their scarcity in ancient deposits can easily be explained not only by their poor preservation potential, but also by the 'nearly terrestrial' habitats of their owners (see Frey and Mayou 1971, p. 58). These habitats, subjected more to erosion than deposition, offer thus extremely low preservational potential, even less than that of rocky shores (cf. Johnson 1988). Only exceptionally can their preservation potential be enhanced by early beachrock diagenetic cementation, as inferred for the succession studied.

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