THE MEDOBORY HILLS (UKRAINE): MIDDLE MIOCENE REEF SYSTEMS IN THE PARATETHYS, THEIR BIOLOGICAL DIVERSITY AND LITHOFACIES

MIODOBORY – ŚRODKOWOMIOCEŃSKI SYSTEM RAFOWY, JEGO ZRÓŻNICOWANIE BIOLOGICZNE I LITOFACJE

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Abstract. The unique Middle Miocene reef belt formed within the Paratethyan realm constitutes at present the Medobory Hills in western Ukraine and northernmost Moldova. Not only is the size of this structure (almost 300 km long) quite unusual, but also the development of peculiar facies and their spatial distribution. Two distinct reef generations appear in Medobory (Late Badenian and Early Sarmatian), both separated by a sharp erosional boundary. Two Upper Badenian calcareous lithofacies dominate – organodetrital and biohermal (with coralline-algae as main framework builders accompanied by a rich invertebrate assemblage). The Lower Sarmatian strata, although megascopically very similar to Upper Badenian ones, differ drastically when studied closely. The main reef components here are serpulids and microbialites, usually with ubiquitous, but taxonomically highly impoverished fauna. Differences in lithofacies and biotic communities between both reef systems unveil open-marine environment during formation of Upper Badenian reefs and a drastic change of conditions at the Badenian/Sarmatian boundary (including emersion and intense weathering). The Early Sarmatian basin was established soon after and highly restricted conditions prevailed in it (e.g. with mesohaline waters and intense evaporation occurring simultaneously); its deposits are the last record of Middle Miocene sedimentation within the Medobory area.

Key words: coralline algae-vermetid reefs, serpulid-microbialite reefs, lithofacies, biodiversity, Badenian/Sarmatian boundary, Ukraine, Moldova.

Abstrakt. Wzgórza Miodoborów, rozciągające się na przestrzeni niemal 300 km na obszarze zachodniej Ukrainy i północnej Mołdawii, założone są na pasie raf miocenu środkowego, uformowanych w obrębie północno-wschodnich peryferii Paratetydy. Znaczne zróżnicowanie litofacjalne, jak i zmienność zespołów biotycznych wśród utworów rafowych jest rezultatem obecności dwóch generacji raf (późnobadeńskiej i wczesnosarmackiej) oddzielonych wyraźną powierzchnią erozyjną. Wśród wapiennych osadów górnego badenu dominują litofacje organodetrytyczne i biohermalne. Ich głównym składnikiem skałotwórczym są krasnorosty, którym towarzyszą bogate taksonomicznie zespoły bezkręgowców, obejmujące m.in. korale, mięczaki, szkarłupnie. Rafy sarmatu dolnego budowane są przez mikrobiality, w obrębie których występują serpule (i podrzędnie mszywioły). Silnie zubożona taksonomicznie fauna zamieszkująca rafy sarmackie zdominowana jest przez mięczaki. Różnice bio- i litofacjalne w obrębie wymienionych generacji raf są efektem drastycznej zmiany warunków sedymentacji, połączonej z emersją i intensywnym wietrzeniem, do której doszło na przełomie badenu i sarmatu w efekcie przebudowy basenu przedkarpackiego. W jej wyniku pełnomorski zbiornik późnobadeński został zastąpiony przez silnie izolowany basen wczesnego sarmatu, zaś powstałe w tym ostatnim osady wieńczą sukcesję utworów miocenu w tej części zapadliska przedkarpackiego.

Słowa kluczowe: rafy krasnorostowo-wermetidowe, rafy serpulowo-mikrobialitowe, litofacje, bioróżnorodność, granica baden/sarmat, Ukraina, Mołdawia.

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INTRODUCTION

The Medobory reefs are unique in the Paratethys Sea. Two generations of the Middle Miocene reefs originating in different environments are distributed widely in the northeastern and eastern borders of the Carpathian Foredeep Basin in western Ukraine, Moldova and north-east Romania (Fig. 1). These reefs provide an excellent opportunity to show how reef-building organisms and reef-dwellers reflected the temporary closure of seaways between the Paratethys and the Mediterranean around the Badenian/Sarmatian boundary.

Coralline algae-vermetid reefs originated in normal marine environments and give evidence for the last marine invasion into western Ukraine during the Late Badenian (Kováč et al., 2007; Studencka, Jasionowski, 2011). Originally full of caverns, provided shelter for numerous reef-dwellers represented mainly by typical epibenthic forms, byssally attached, and those cementing to the substrate.

The connection between the Mediterranean and the Central Paratethys was interrupted in the latest Badenian. Probably only a narrow strait existed at that time, linking the Paratethys with the Mediterranean, located in the present-day Bosphorus region (Popov et al., 2004). The Badenian/Sarmatian boundary witnessed fundamental reorganization of the Paratethys palaeogeography. The Carpathian Foredeep Basin constituting since the Kiscellian the northern part of the Central Paratethys became a marginal basin of the Eastern Paratethys (Fig. 2), showing stronger influence of its water masses (cf. Studencka, 1999; Studencka, Jasionowski, 2011). At the same time a significant faunal reorganization also occurred, as inferred from drastically reduced diversity of faunal assemblages and absence of marine stenohaline taxa. The separation of the Paratethys is indicated also by the vast development of endemic species (Paramonova, 1994; Popov et al., 2005; Harzhauser, Piller, 2007; Roshka, 2008; Nevesskaja et al., 2009; Studencka, Jasionowski, 2011).

The process, which led to the separation of the Paratethys from the Mediterranean and formation of the peripheral Galician Bay, resulted in the development of extremely stressed environments related to mesohaline salinity, elevated alkalinity and eutrophic conditions. At that moment, the development of serpulid-microbialite reefs started, characterised by distinct ecological, biological and sedimentological aspects (Jasionowski et al., 2003; Jasionowski, 2006).

The main objective of this paper is to present the lithofacies of the Upper Badenian coralline algae-vermetid reefs and Lower Sarmatian serpulid-microbialite reefs as well as their biological diversity.
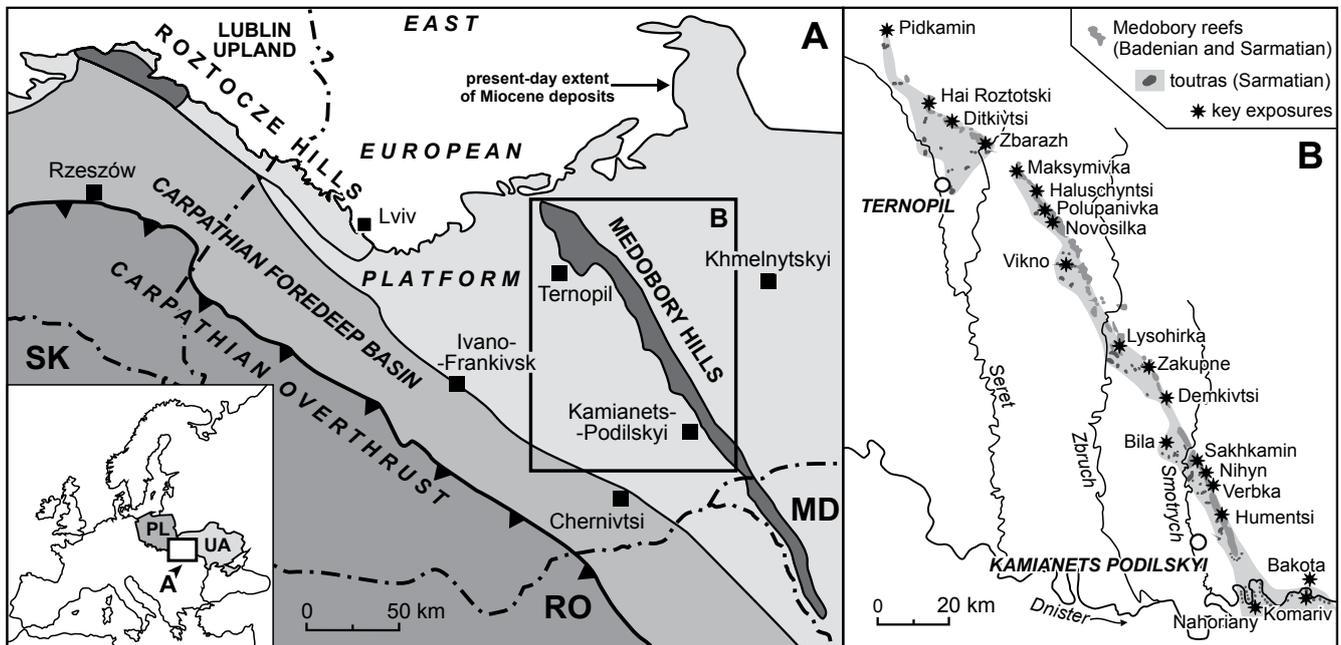
Fig. 1. A – Map of Middle Miocene deposits in the Carpathian Foredeep Basin in Poland and Ukraine, showing distribution of reefal deposits (solid shading); B – Location and distribution of the Badenian and Sarmatian reefs of the Medobory Hills (after Korolyuk, 1952; modified)
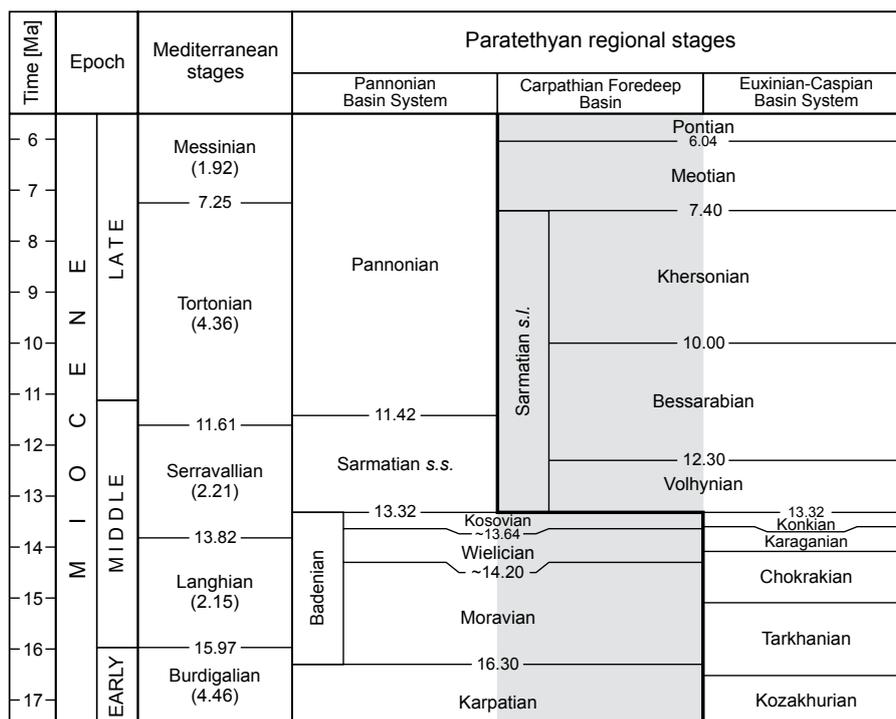
Fig. 2. Correlation chart of the Miocene regional stages of the Central and Eastern Paratethys and Mediterranean provinces (after Studencka, Jasionowski, 2011)

PREVIOUS STUDY OF MEDOBORY

The pioneering study of the excellently exposed Medobory reefs was carried out at the end of the 19th century. The western part (west of the Zbruch River) was studied in detail by Hilber (1882) and Teisseyre (1884, 1895, 1900) as part of the geological mapping of Galicia (from 1873 to 1914 being an autonomous province of the Austrian part of the Dual Monarchy). The eastern part was studied by Laskarew (1903, 1914) as part of the geological mapping of the Russian Empire.

It was the impetus for rigorous geological examination and interpretation of depositional history of Medobory reefs (Siemiradzki, 1909). Synthetic sedimentological and stratigraphical studies encompassing data from Medobory reefs in Ukraine were undertaken by Korolyuk (1952), Maslov, Utrobin (1958), Kudrin (1966) and Vialov (1970). Data concerning stratigraphy of Medobory reefs in Moldova were presented by Roshka, Khubka (1981), whilst the publications of Voloshina (1973) and Janakevich (1969a, b, 1977, 1993) attempted systematic account of their reef-dwellers. Recently, Petryczenko *et al.* (1994) and Andreyeva-Grigorovich *et al.* (1997) presented a summary of lithostratigraphy of the Ukrainian part of the Carpathian Foredeep Basin including Medobory (Fig. 3).

Fig. 3. Schematic lithostratigraphic division of Miocene deposits of the Medobory area (after Petryczenko *et al.*, 1994, Andreyeva-Grigorovich *et al.*, 1997)
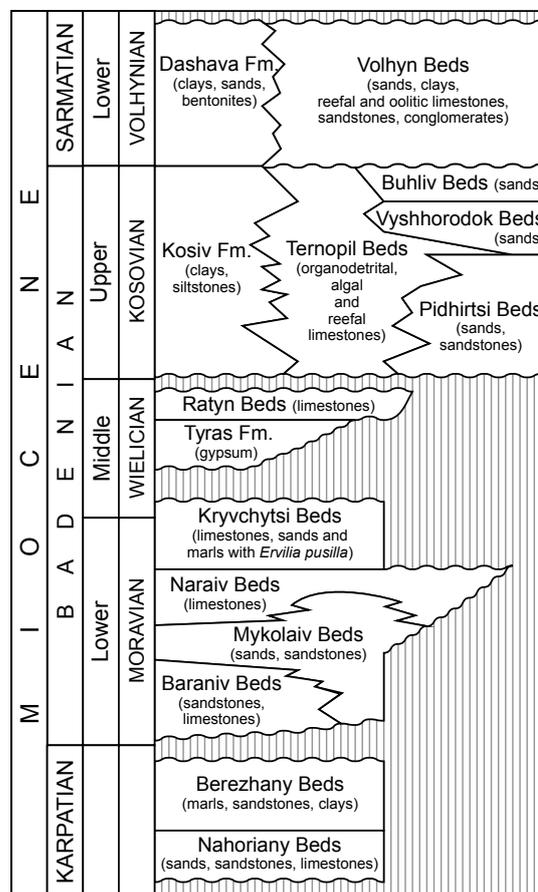
GEOLOGICAL SETTING

Medobory Hills are located in the SW margin of the Eastern European Platform, also known as the Podolian Plateau. Above the Precambrian crystalline basement (exposed more easternward at the Ukrainian Shield) there are almost horizontal uppermost Precambrian (Vendian), Paleozoic (Cambrian to Devonian) and Mesozoic (mainly Cretaceous) beds. A relatively thin succession of Miocene (Karpatian, Badenian and Sarmatian) deposits was accumulated in a shallow-marine environment. The youngest strata are Pleistocene (loess) and Holocene (fluvial) deposits.

The Miocene succession is usually developed over the Silurian and/or Cretaceous bedrock. Due to the migration of sedimentary axis, caused by tectonic evolution of the Carpathians, the extent of the sea increased rapidly at the boundary of the Middle and Late Badenian (Late Badenian transgression), reaching a few tens of kilometres eastward onto the Eastern European Platform. It caused an onlap of Upper Badenian deposits over the older strata. In the Medobory area, which was located outside main tectonic frames of the Carpathian Foredeep Basin, the Middle Miocene succession is represented by Upper Badenian and Lower Sarmatian deposits only. The older Miocene strata (Karpatian, Lower

and Middle Badenian) are present to the SW of Medobory, whereas younger, Middle Sarmatian rocks, are exposed over 50 km to the east (Kudrin, 1966).

The lowermost part of the Middle Miocene succession is usually represented by sandy deposits with rich open-marine fauna (Pidhirtsi Beds), overlain by or interfingering with carbonate facies (biohermal and organodetrital) of the Ternopil Beds (e.g., Gedl, Peryt, 2011) being the main lithofacies unit within the Medobory structure (Fig. 4).

On the north-eastern side of the Medobory Hills, the Ternopil Beds are covered by greenish glauconitic quartz sands with open-marine fauna (Vyshhorodok Beds), passing upward into sandy deposits of the Buhliv Beds with a strongly impoverished biotic assemblage.

An erosional gap, developed over the Ternopil Beds, divides the Upper Badenian deposits from the Lower Sarmatian (Volhynian) strata of the Volhyn Beds. These represent a strongly differentiated lithologically complex of calcareous (serpulid and microbialite reefal limestones, oolites, marls) and terrigenous (sand and clay) deposits containing a typical Early Sarmatian impoverished faunal assemblage of bivalves, gastropods, benthic foraminifers and bryozoans.
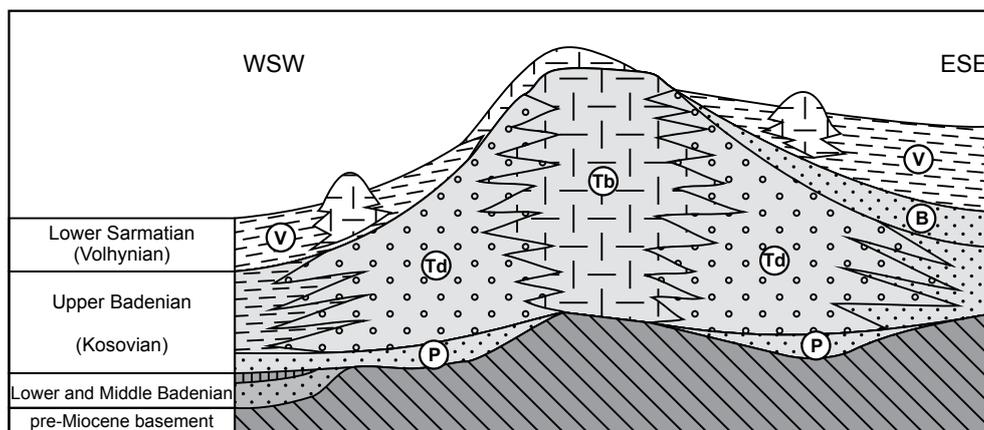
Fig. 4. Schematic geological cross-section through Medobory

Abbreviations: P – Pidhirtsi Beds, Tb – Ternopil Beds (biohermal facies), Td – Ternopil Beds (detrital facies), B – Vyshhorodok Beds and Buhliv Beds, V – Volhyn Beds (after Jasionowski *et al.*, 2006)

THE REEFS OF MEDOBORY

As mentioned above, Middle Miocene reefs of the Medobory area represent two generations of reefs originating in different environments in the Late Badenian and Early Sarmatian seas. Possibly that is why each reef system is characterised by very particular lithofacies composition, faunal assemblage, and geochemical features. These differences were caused by various palaeoecological conditions during the formation of reef systems.

In the literature, there is a variety of names for the reefal structures and hills. In the present paper, a nomenclature proposed by Korolyuk (1952) is applied. According to this, only

a chain of hills built of the Upper Badenian reefs is treated as Medobory, that could be (although not always) overlain by Sarmatian deposits (often reefal), while the Lower Sarmatian reefs are known as "toutras"[1] – rocky hills, well marked in topography, usually located in the SW foreland of Medobory (open-sea side), sometimes also covering the top of the Upper Badenian reefs (Figs. 5, 6).

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[1] The etymology comes from the village of Toutry near Skalat, where isolated hills of peculiar shape, built of the serpulid-microbialite reefs, are especially well exposed.
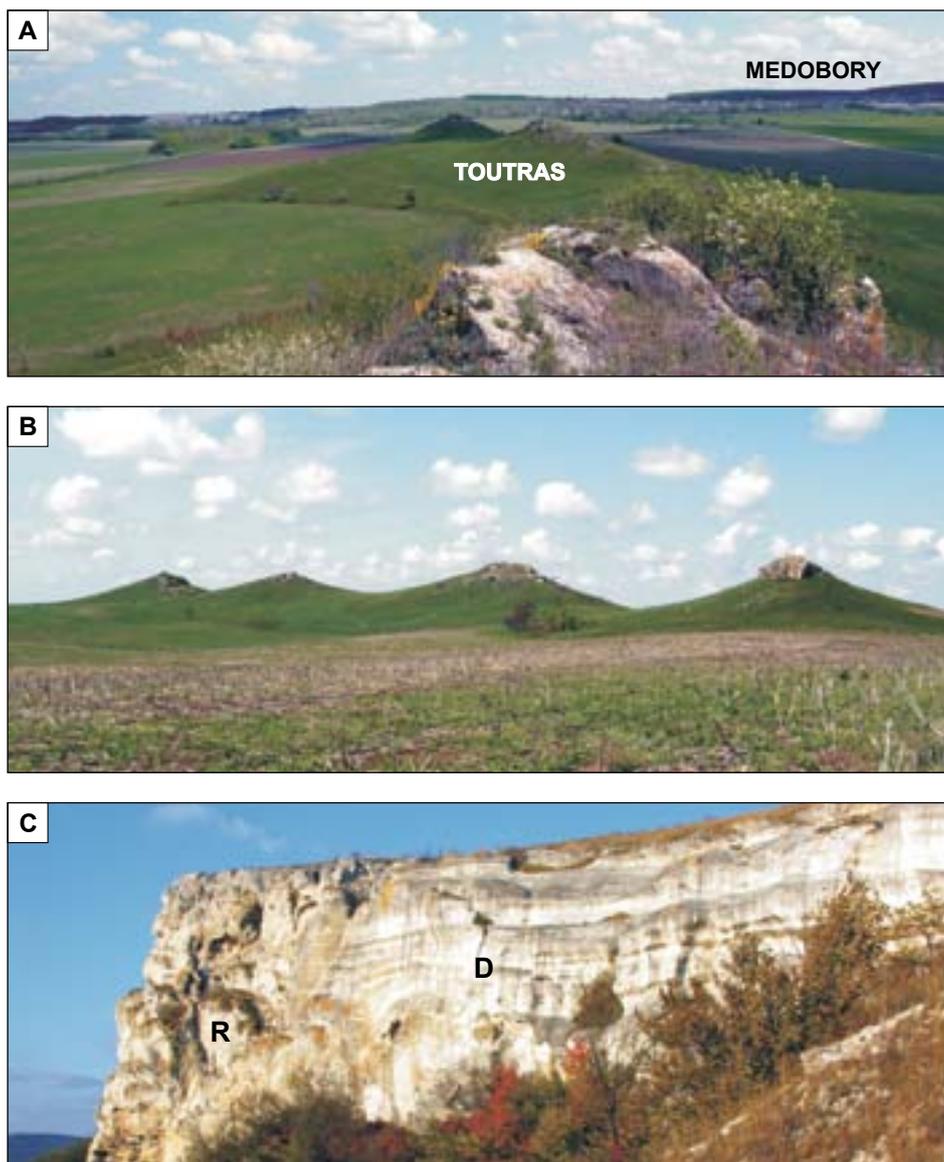
Fig. 5. Field-images of selected Medobory localities, to show the formation and spatial distribution of lithofacies

A – overall view of the Verbka vicinity showing spatial relationship between the Medobory Hills and chain of toutras; **B** – view of chain of toutras in the Verbka vicinity; **C** – panoramic view of the Bakota site, note the sharp boundaries between the Upper Badenian reefal (R) and detrital (D) lithofacies

LATE BADENIAN REEFS

The Upper Badenian reefs of Medobory formed a relatively narrow (a few km wide, rarely up to 40 km) and 300 km long belt (which is clearly a barrier reef and is still visible in the present-day morphology), that separated deeper environments of the Carpathian Foredeep Basin with marls and clay deposition from the nearshore siliciclastic facies, discordantly overlying the pre-Neogene basement (Maslov, Utrobin, 1958).

This belt consists predominantly of Upper Badenian coralline-algae boundstones and bioclastic grainstones/rudstones (Korolyuk, 1952; Janakevich, 1977; Jasionowski, 2006), reflecting the environmental variability within a reefal belt (Figs 7, 8 A–E). Massive boundstones represent the main reef bodies (reef-core facies) with a thickness exceeding 100 m in axial parts. The most important rock-forming element is encrusting red algae of the family Corallinaceae. Another, subordinate elements are sessile gastropods of the family Vermetidae. Due to their abundance, the facies (especially of the Roztocze area) is often referred to as algal-vermetid reefs (see Pisera, 1985). Quite ubiquitous are hermatypic corals; this fact distinguishes the reefs from those of Roztocze where corals were not recorded. In addition, parts of reefs are built of locally abundant bryozoans, gastropods, and/or oysters.

Other organisms associated with reefs are represented by a taxonomically rich assemblage of bivalve molluscs and marine gastropods, crustaceans (crabs), foraminifera, annelids, bryozoans, and echinoderms (sea urchins). Almost all of the organisms of originally aragonitic shells were dissolved as a result of postsedimentary diagenesis and are now pre-
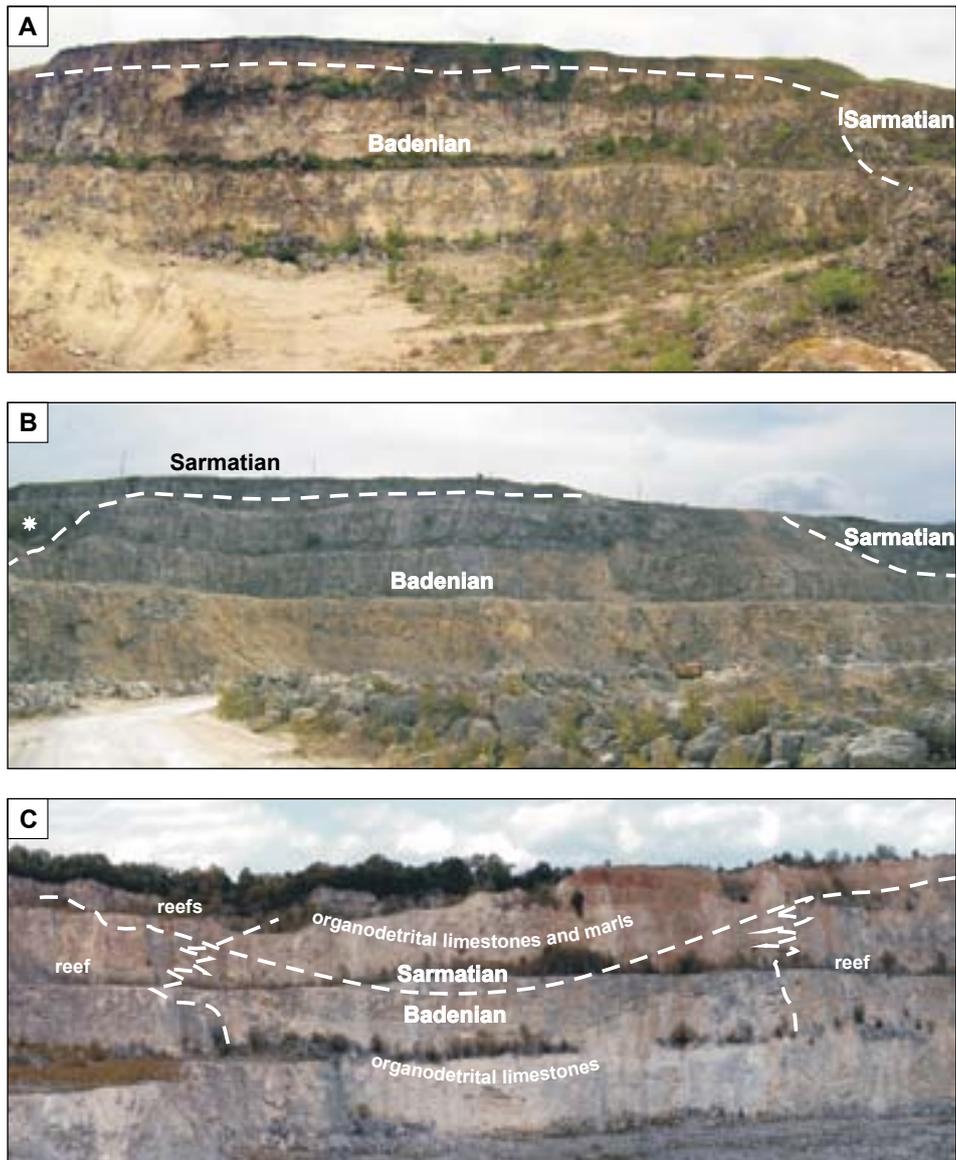
Fig. 6. Field-images of selected Medobory quarries, to show spatial lithofacies distribution

A – panoramic view of the eastern wall of the Maksymivka quarry; note the flat eroded top of the Upper Badenian reef passing into a steep erosional surface of the Badenian/Sarmatian contact; **B** – panoramic view of the eastern wall of the Haluschyntsi quarry; note the presence of thick complex of Lower Sarmatian conglomerates (asterisked) above the eroded Upper Badenian reef; **C** – panoramic view of the northern wall of the Humentsi quarry showing depositional architecture of main reefal lithofacies

served in the form of moulds and/or imprints. It most often refers to molluscs, whose shells (except of calcite shells of oysters, scallops, and related taxa) are almost always completely dissolved.

High porosity is a typical feature of boundstone facies. The primary pores are of different origin and sizes (from millimetres to several tens of cm and larger) and may be empty or filled with sediment. Small vugs (up to several cm) related to irregular growth of red algae thalli are often filled with micritic material (calcareous mud). Larger vugs, crevices, and notches in the reef relief are usually filled with organodetrital material, which consists of skeletal debris of reef-dwelling invertebrates. Field observations have also shown the presence of breccias, vadose silt and vadose leaching in

the uppermost coralline-algae boundstones, indicating considerable sea-level fluctuations and a phase of emersion of the Medobory reefs in the latest Badenian (Studencka, Jasionowski, 2011; Peryt, Jasionowski, 2012). Another result of synsedimentary destruction of the reefs may also be observed, as the slopes of reef-bodies are often covered with breccias and conglomerates.

Reefal build-ups (bioherms) usually intercalate and interfiger with rhodoid and bioclastic facies. Those bedded organodetrital deposits fill the pits in the relief of bioherms; they are also commonly present in interreefal parts of the reef-belt as well as in fore-reef and back-reef areas, but their extent does not usually exceed the lateral distance of approximately 20 km.
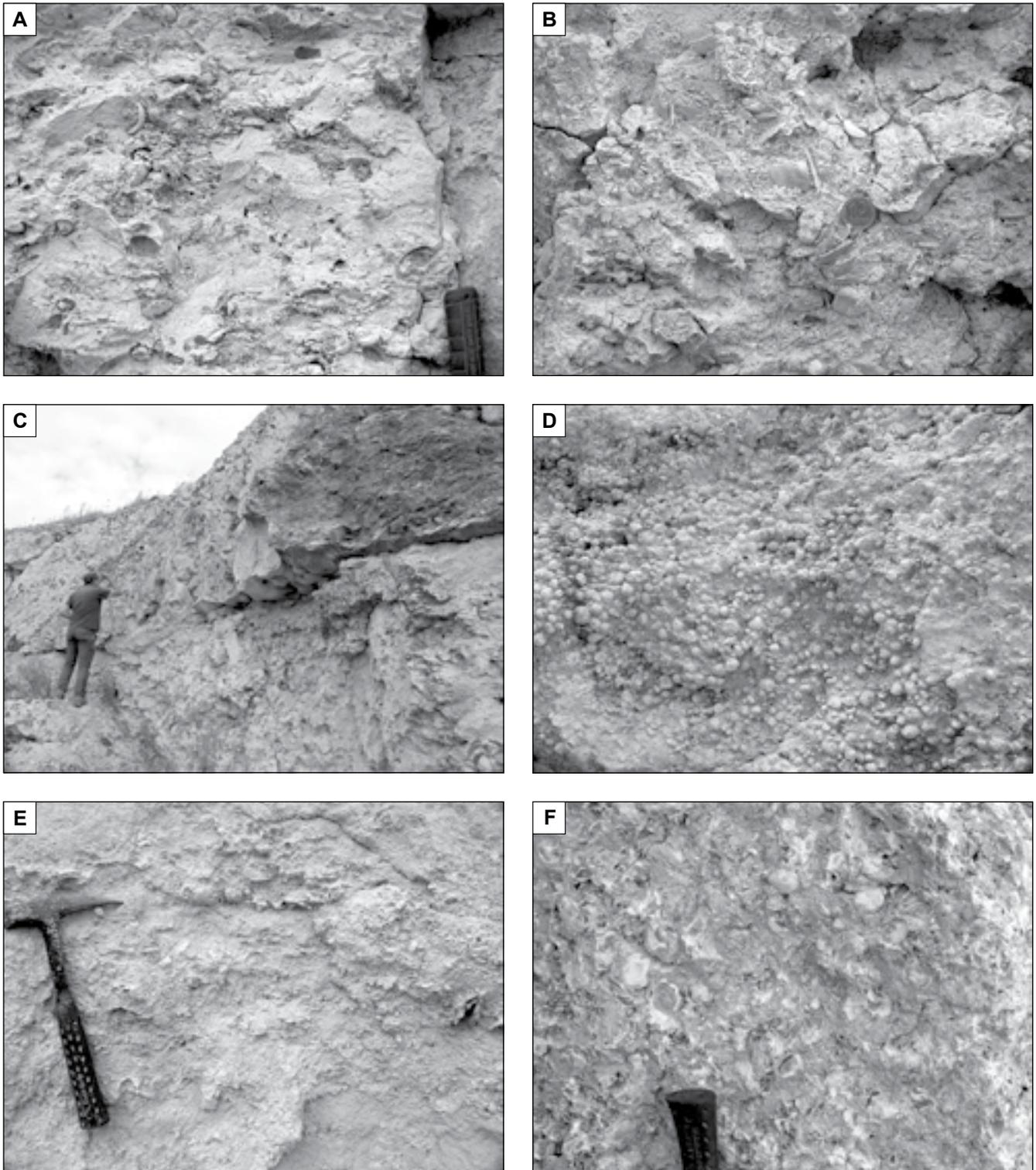
Fig. 7. Details of Upper Badenian facies of Medobory

A – massive coralline-algae boundstone with embedded *Haliotis* shells, Maksymivka; **B** – fissure within a reefal boundstone filled with coarse organodetrital material with abundant scallop shells, Haluschyntsi; **C** – internal boundary within a reefal build-up: two generations of boundstone (the upper one is more massive) clearly visible, Demkivtsi; **D** – organodetrital deposits with mass-accumulated rhodoids, Nihyn; **E** – coarse-grained organodetrital deposits, Nihyn; **F** – oyster biostrome built of mass-aggregated *Neopycnodonte navicularis* (Brocchi), Hai Roztotski
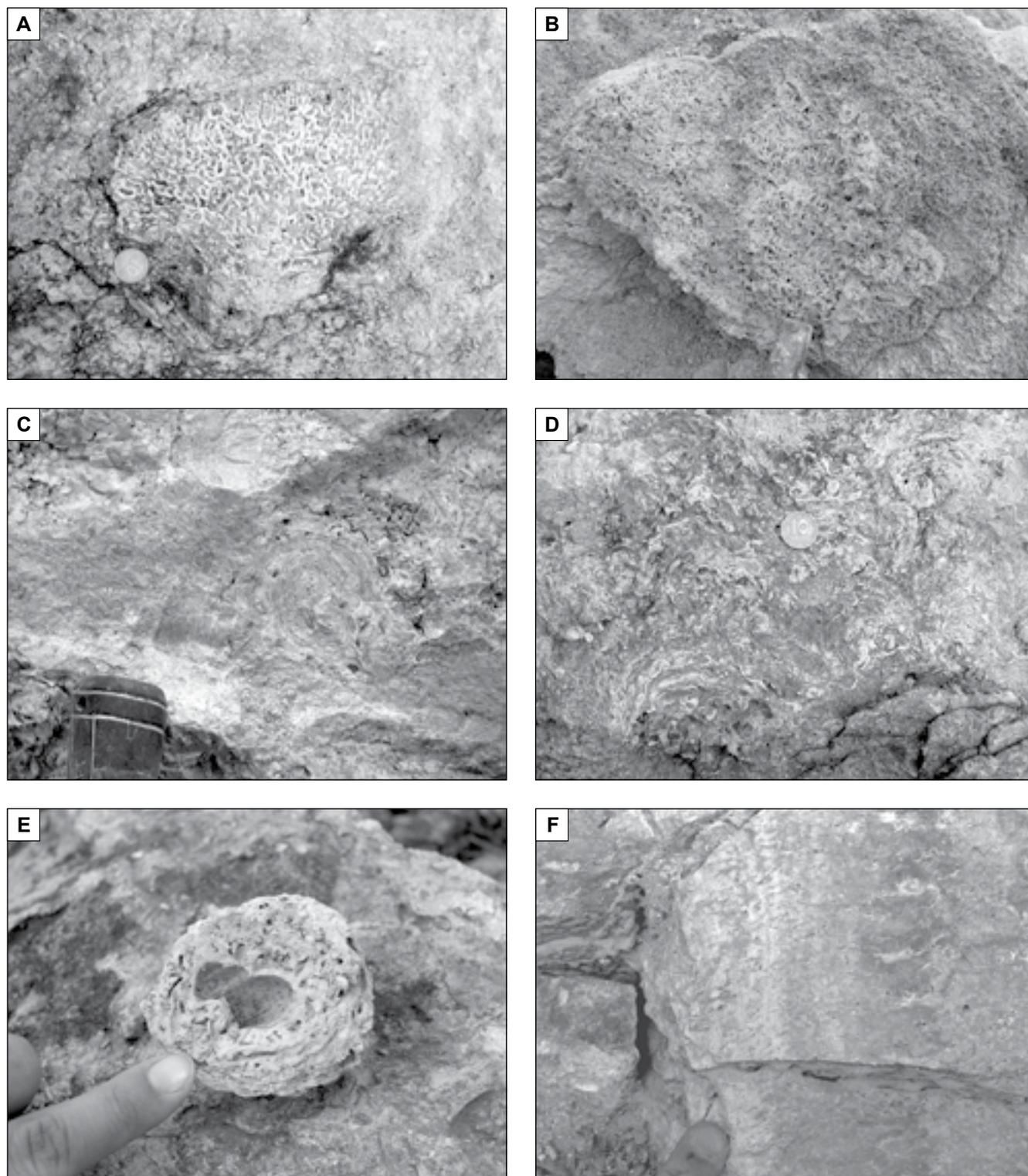
Fig. 8. Crustose coralline algae constructing the Upper Badenian (A–E) and Lower Sarmatian (F) reefs of Medobory

A, **B** – branching coralline-algae thalli from reefal boundstone facies (A – Maksymivka, B – Hai Roztotski); **C**, **D** – massive laminar coralline-algae thalli from reefal boundstone facies (C – Sakhkamin, D – Humentsi); **E** – isolated rhodoid from reef-slope deposits, Nihyn; **F** – coralline algae crust within serpulid-microbialite reef limestone, Polupanivka

Organodetrital facies at its bottom and in the intermediate neighbourhood of reefal build-ups contains numerous rhodoids of diameter often exceeding 10 cm. Some parts of rock (especially in lowermost parts of the profile) have a significant number of marly intercalations. The matrix of rock is composed of coralline-algae debris with skeletal remains of invertebrates. Among the latter, relatively well-preserved calcitic shells of oysters and scallops, as well as fragments of echinoid tests could be found. More upward and with the increase in the distance from bioherms, rhodolithic subfacies passes gradually into coarse limestone (calcarenites/calcirudites). More fine-grained varieties of these limestones can be commonly observed; their amount usually increases with the distance from reefs.

EARLY SARMATIAN REEFS

The Early Sarmatian reefs usually overgrow an eroded and karstified surface of the Badenian reefs, reaching the greatest thickness in the south-western slopes of Medobory (Fig. 9).

Reefs are also found as patches of rocky hills among marly-clayey deposits outside the Medobory belt, at the south-western (open-sea) side of the main reefal belt (Korolyuk, 1952). They are usually arranged in gently curved linear chains oriented approximately perpendicular to Medobory (see Fig. 5). Small bioherms may be also found in back-reef (lagoonal) areas.

The most characteristic lithofacies of the Sarmatian reefs is serpulid-microbialite limestone (Figs. 10, 11) (Jasionowski, 2006). It is hard and very porous (primary porosity) limestone, brownish on its fresh surfaces. Its main component is micrite that builds microbialites. Primary growth pores are usually lined by fibrous synsedimentary cements and filled with micritic internal sediments. Small serpulids (tube diameter of about 1 mm, length up to several cm), probably of the genus *Hydroides* Gunnerus (Korolyuk, 1952; Pisera, 1978), are subordinate components (up to a few percent by volume of rock). Small branching bryozoans are less frequent.

Other lithofacies play a subordinate role in the Lower Sarmatian reefs. Among them, coquinas are of the most importance. Those are relatively common at the base and on the slopes of reefs. Shells are usually cemented with synsedimentary fibrous cements; shells are sometimes embedded within calcareous muddy matrix.

During their development, the reefs had undergone synsedimentary erosion. As a result, breccias and conglomerates made up of bits of the Sarmatian reefal limestone (often also Badenian) formed. Clasts usually may be coated with encrusting organisms (e.g. bryozoans) and microbialite layers. Bituminous "black pebbles" built of serpulid-microbialite limestone, typical of shallow coastal anoxic environments, are often found among coarse detrital material (Fig. 20E, F).

Synsedimentary precipitates (microbialites and fibrous cements) are characterized by unusual geochemical charac-teristics. They are composed of Mg-calcite with relatively low Mg content (5–6 mol% $MgCO_3$) and high Sr concentrations (about 1500 ppm), and are highly enriched in heavy isotopes of carbon and oxygen, indicating the precipitation from waters that underwent considerable evaporation (Jasionowski, 2006).

Biotic assemblages of the Sarmatian reefs are relatively poor taxonomically, but represented by extremely numerous specimens. Besides serpulids and bryozoans, other skeletal organisms are of a little importance as reef constructors. Nevertheless, they can be divided into two groups.

The first group includes encrusting organisms: coralline algae, sessile foraminifers (nubecularids) and multilamelar bryozoans of the genus *Schizoporella* Hincks.

The members of the second group are organisms that did not participate in the construction of the reef framework, and were dwellers of a rocky-bottom habitat only. This assemblage is dominated by bivalves (Studencka, Jasionowski, 2011); several taxa of gastropods, bryozoans, foraminifers and ostracods were also found. Numerous remains of these organisms, together with epiphytic bryozoans, appear in large growth cavities within a reef body.

Other Lower Sarmatian lithofacies, intercalating and interfingering reefal deposits, are bedded marls and organodetrital limestones. Those gradually pass into open-marine clayey strata (SW of Medobory) or into clayey/sandy and oolitic facies of a back-reef ("lagoonal") area.

REEF ORGANISMS

Coralline algae
(Figs. 7D, 8)

Coralline algae are the main component of the Upper Badenian reefs, showing a wide variety of growth forms – from laminar to branching. Their taxonomic composition in the Medobory reefs was investigated by Maslov (1962) who stated the presence of numerous genera and species. Some ambiguities concerning the species and varieties erected by Maslov were discussed by Studencki (1988a). Such genera as: *Sporolithon* Haydrich (formerly *Archeolithothamnium* Foslie), *Lithothamnion* Haydrich (formerly *Lithothamnium* Philippi), and *Lithophyllum* Philippi are dominant and played an important role in influencing the depositional environment by producing particulate sediment and by binding and trapping fine detritus. After creation of the new classification of coralline algae (Woelkerling, 1988), a revision of Maslov's taxonomic designations is necessary (similarly as in the Roztocze area, where genus *Spongites* Kützing is currently applied for many algae that were previously ascribed as *Lithophyllum* – see Jasionowski, Wysocka, 1997).

Environmental changes around the Badenian/Sarmatian boundary strongly affected this group of organisms. In the Lower Sarmatian reefs, coralline algae are a subordinate element – they are represented only by encrusting species belonging most probably to the genus *Titanoderma* Nägel (Fig. 8F).
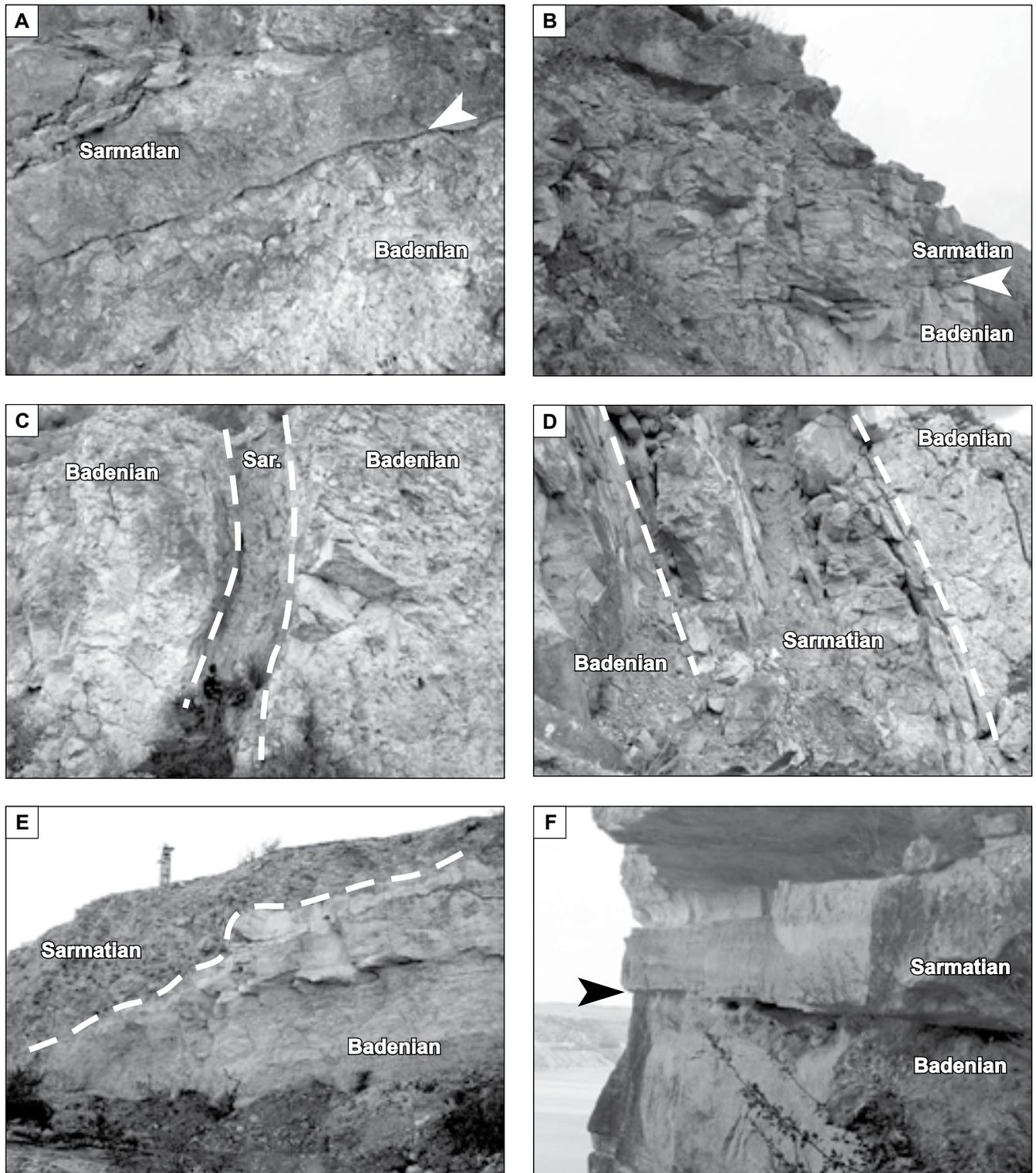
Fig. 9. Details of the Badenian/Sarmatian boundary at Medobory

A, **B** – sharp erosional boundaries (arrowed) between Upper Badenian coralline-algae and Lower Sarmatian microbialite boundstones (A – Ditkivtsi, B – Maksymivka); **C**, **D** – varied-sized erosional fissures within the Upper Badenian reefs filled with Lower Sarmatian microbialite limestone (C – Nihyn, D – Maksymivka); **E** – sharp erosional boundary between coarse-grained bedded Late Badenian calcarenites and Early Sarmatian massive conglomerates, Humentsi; **F** – Badenian/Sarmatian boundary (arrowed) within a fine organodetrital back-reef facies, Komariv upon Dnister
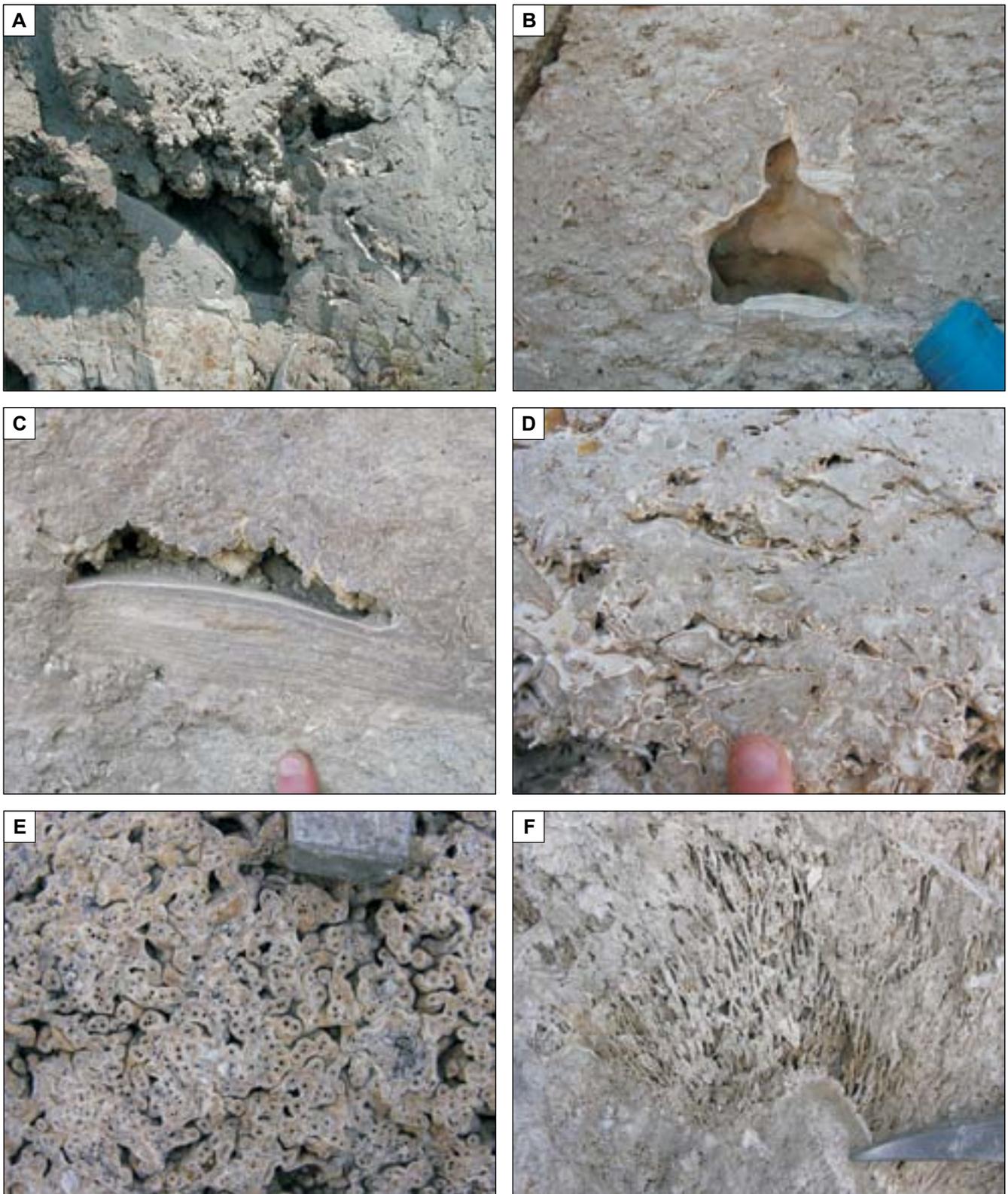
Fig. 10. Various lithologies of Sarmatian serpulid-microbialite reef limestones

A – large growth cavity between hemispherical reefal bodies with miritic geopetal internal sediment at the bottom, Bila; **B** – massive reef limestone with a single growth cavern rimmed with thick synsedimentary cement, Hai Roztotski; **C** – small growth cavity in reef limestone with internal sediment at the bottom, Ditkivtsi; **D** – cavernous limestone with no internal sediments; Vikno; **E** – a serpulid tubes tangle encrusted by thick rims of synsedimentary cement, Vikno; **F** – bunch of parallel serpulid tubes, fan-like arranged and embedded within reef microbialite limestone, Vikno
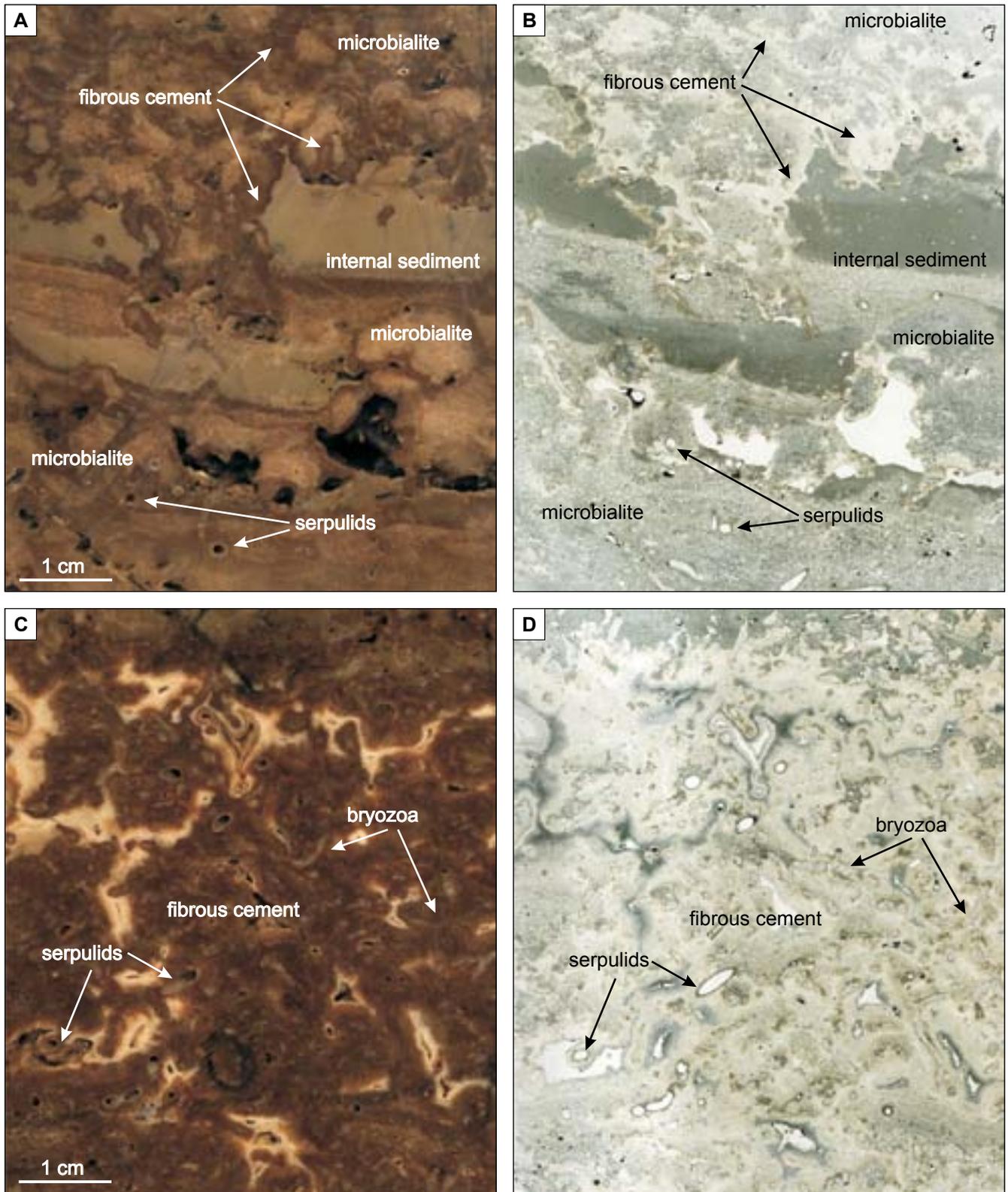
Fig. 11. Typical serpulid-microbialite boundstone with microbialites growing on serpulid tubes, and growth cavities filled

A, B – with internal sediment and synsedimentary fibrous cement, scanned slab (A) and equivalent thin section (B), Bila; C, D – with serpulid-microbialite boundstone with abundant framebuilding branching bryozoans, pervasive synsedimentary fibrous cements and very minor microbialites, scanned slab (C) and equivalent thin section (D), Bila

Corals
(Fig. 12)

Colonies of hermatypic corals are other significant components of the reef-core facies. However, the occurrence of coral-built framework has never been observed by the authors in the investigated outcrops. It corresponds with observations of Dembińska-Różkowska (1932) who noticed only one case of coral-built framework in the Medobory area. Single colonies are often observed distributed among the coralline algal framework. Aragonitic colonies are usually dissolved and/or neomorphised, only several investigated specimens seem to occur in original state of preservation. Taxonomic composition of the coral assemblage is dominated by two species: *Tarbellastraea reussiana* (Milne-Edwards *et* Haime) and *Porites vindobonarum prima* (Kühn). Among these species, a bunch of morphological varieties is observed. Morphology of the colonies varies from encrusting through massive to branching, stick-like forms. Encrusting colonies, most often of *P. vindobonarum prima*, up to a few centimetres thick, are usually overgrown by coralline algae thalli. Massive colonies may reach over 10 centimetres in *P. vindobonarum prima* and almost 50 cm in *T. reussiana*. Branching colonies of *P. vindobonarum prima* are built of sticks of diameter about 2 cm and up to 20 cm high, while sticks of *T. reussiana* may reach as much as 5 cm in diameter and 50 cm in height. Two other taxa of hermatypic corals were also noticed: *Siderastrea* cf. *italica* (Defrance) and ?*Montastrea* sp. Compared to the previous taxa, the latter ones must be considered as extremely rare. Taxonomic composition of the investigated coral assemblage shows significant similarity with other Miocene coral reefs of the Tethys (Esteban, 1996; Esteban *et al.*, 1996; Hayward *et al.*, 1996) and Paratethys (Friebe, 1991; Müller, 1996; Riegl, Piller, 2000; Górka, 2002). None of the mentioned coral taxa survived the Badenian/Sarmatian boundary in Medobory, as no corals have ever been observed in the Lower Sarmatian deposits.

Bryozoans
(Figs. 13, 14)

The distinctive Late Badenian bryozoan assemblage is documented from the calcareous and the clastic sandy and silty deposits in the Haluschyntsi quarry. This assemblage of an average biodiversity of 30 different taxa in comparison to the richest bryozoans biota described from the Badenian of Hungary composed of 238 taxa (Moissette *et al.*, 2006) and 191 recorded from Poland (Małecki, 1952, 1958, 1978; Vavra, 1984; Pouyet, 1997), has proved a new bryozoan record. The very characteristic colonies in this biota are cyclostomes dominated by the massive zoaria of erect, spheroidal colonies of the family Cerioporidae Reuss represented by *Bobiesipora fasciculata* (Fleming). The genus *Bobiesipora* Vavra possesses the zoarium which consists of a circular or oval-shaped base, completely covered with kenozooecia, with the branches developing in radially arranged fascicles similar to those of the family Lichenoporidae, represented by *Disporella hispida* (Fleming) with a prominent, centrally placed gonozooecium, and the other species of *Lichenopora* Defrance present in the studied assemblage. Among the cyclostomes, there are also small, finger-shaped, encrusting zoaria of *Crisia elongata* Milne-Edwards, sometimes coil-shaped zoaria of *Tubulipora flabellaris* (Fabrucius), and encrusting zoaria of *Oncousoecia* Canu and *Plagioecia* Canu.

The cheilostomes are the most common component in the Haluschyntsi assemblage. They are abundantly represented by the family Myriaporidae Gray of the erect, irregularly branching colonies of *Myriapora truncata* (Pallas), and the other encrusting bryozoans such as *Hippopleurifera semicristata* (Reuss) and *Schizoporella tetragona* (Reuss) that is the most common frame-builder bryozoan in the Medobory reefs. The colonies of *Steraechmella buskii* Lagaaij, ?*Lunulites* Lamarck and *Cupuladria* Canu-Bassler also occur. The very characteristic colonies are *Reteporella* sp. belonging to the family Phidoloporidae Gabb *et* Horn. Its reticulated zoaria are the characteristic component of the bryozoan fauna of the coralligenous biocenose, being the richest circumlittoral bryozoan adopted for life in the regions where wave currents are strong.

The Late Badenian bryozoan assemblage is also rich in branched cheilostome colonies of *Steginoporella* Smitt and encrusting *Rhamphonotus* Norman. The large palm-shaped, encrusting, branching or massive globular zoaria belong to *Celleporaria palmata* (Michelin) whose colonies may exceed a few cm in height. They are a very distinct element of the Medobory biota.

The bryozoans are an important constituent of the Lower Sarmatian deposits of western Ukraine (Bagdasarjan, Ponomarieva, 1982). Their spatial distributions, colony growth pattern, and the relationship of the bryozoans in the Sarmatian biocenosis within the reefs are very differentiated. Eighteen bryozoan species have been recognized within the reef, organodetrititic and silty-marly facies. The distribution pattern of bryozoans in the carbonate buildups is patchy and their role as a frame-builder is limited, however, the bryozoans are one of the most conspicuous elements in the algae-dominated cryptic microhabitats where they form superposed overgrowing layers.

Schizoporellids, represented by the *Schizoporella tetragona* (Reuss) in the Medobory ecosystem, perform the main constructional role. They form multilamellar biostructions, variable in shape and size, composed of numerous, sometimes densely packed layers that usually show rhythmic growth and also mark a few sequences of laminae, varying in thickness from 0.36 to 1.4 cm, which may indicate sedimentological cycles related probably to the fluctuation within the sedimentary environment of the Sarmatian basin. The very characteristic feature of *Schizoporella tetragona* (Reuss) within the Medobory reefs is the great plasticity of the colony form, showing different morphotypes varying in construction from unilamellar and branching up to multilamellar, related directly to the environmental factors. It is characteristic that usually this multilamellar morphotype occurs in the spatially restricted, transitional, geologically short-term settings, which most of the bryozoans are not able
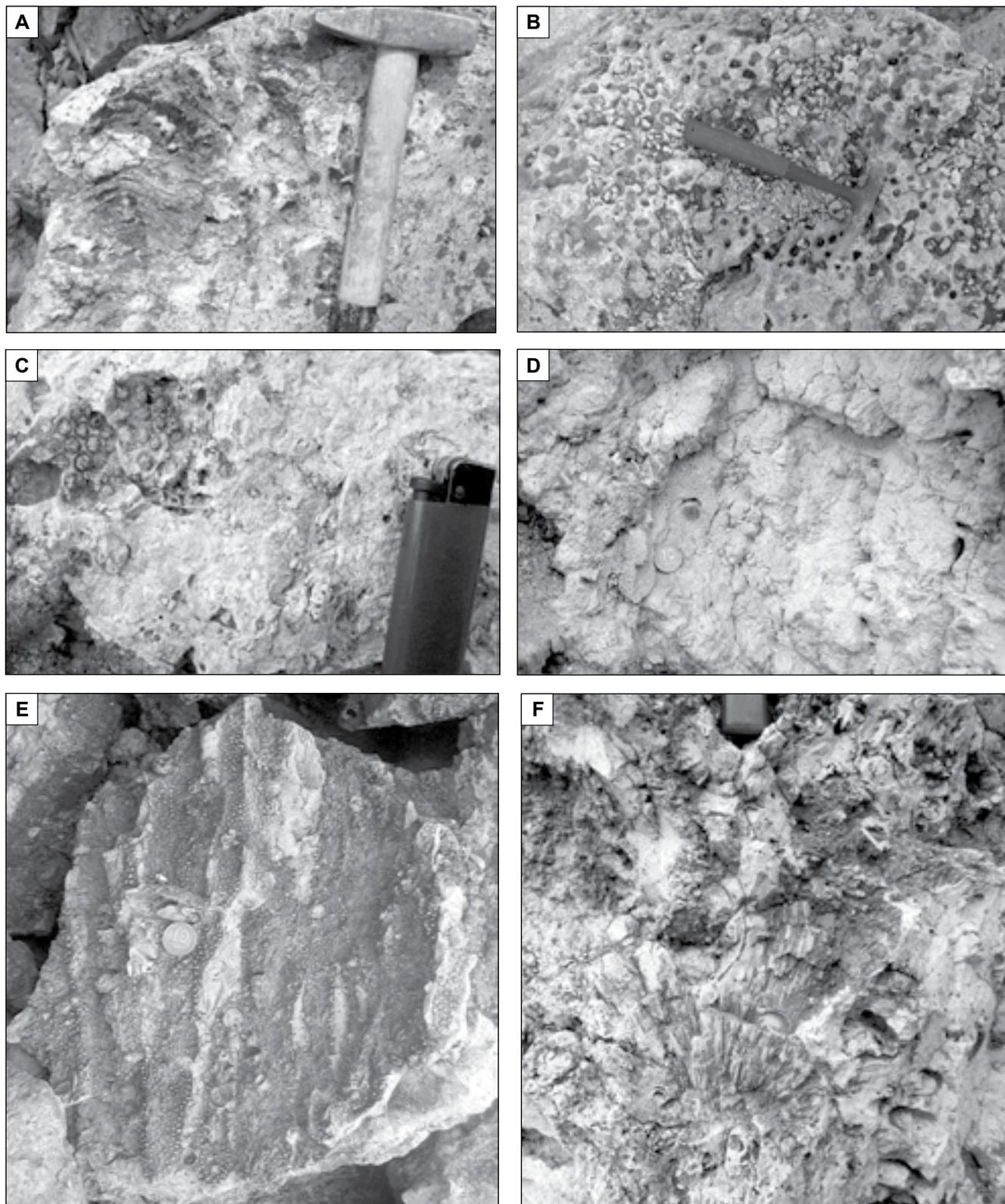
Fig. 12. Hermatypic corals from the Upper Badenian reefs of Medobory

A – massive colony of *Porites vindobonarum prima* (Kühn), Demkivtsi; **B** – mass-occurrence of branching colonies of *Porites vindobonarum prima* (Kühn), Sakhkamin; **C** – mould of *Montastrea* sp., Zakupne; **D** – massive colony of *Tarbellastraea reussiana* (Milne-Edwards *et* Haime) with bivalve borings, Halushyntsi; **E** – large branching colony of *Tarbellastraea reussiana* (Milne Edwards *et* Haime) with numerous bivalve borings, Maksymivka; **F** – *Siderastrea* cf. *italica* (Defrance) with bivalve borings, Demkivtsi
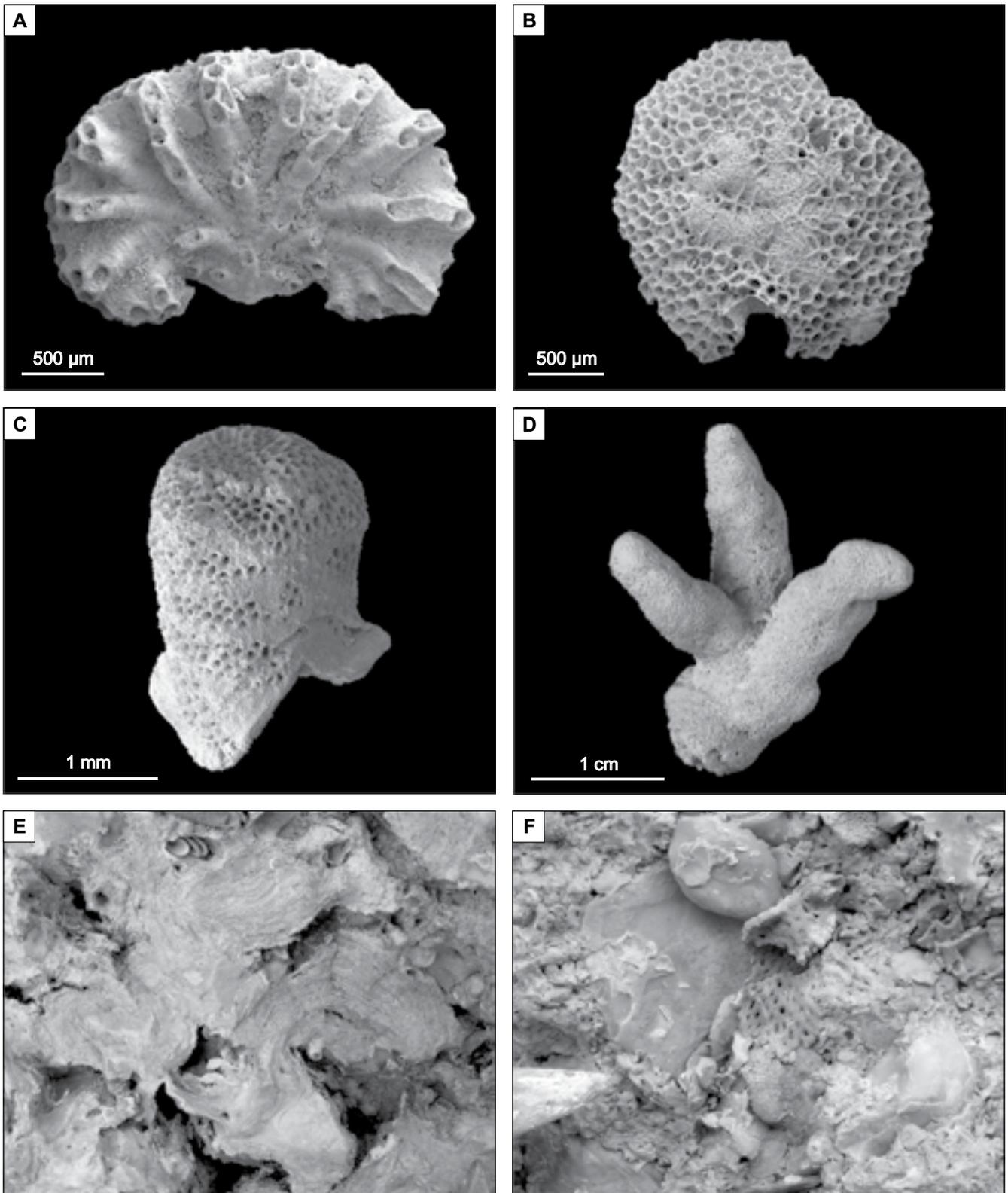
Fig. 13. Upper Badenian bryozoans from the coralline algae-vermetid reefs

A – encrusting zoarium of *Tubulipora flabellaris* (Fabricius); **B** – frontal wall of *Disporella hispida* (Fleming), with the centrally placed ovicell; **C** – fragment of a robust, erect colony of *Bobiesipora fasciculata* (Reuss), showing the basal part; **D** – view of a palm-shaped colony of *Celleporaria palmata* (Michelin); **E** – a few clumps composed of multilmellar colonies of *Schizoporella tetragona* (Reuss); **F** – fragment of reticulate colony of *Reteporella* sp.; A–D Haluschyntsi, E–F Hai Roztotski
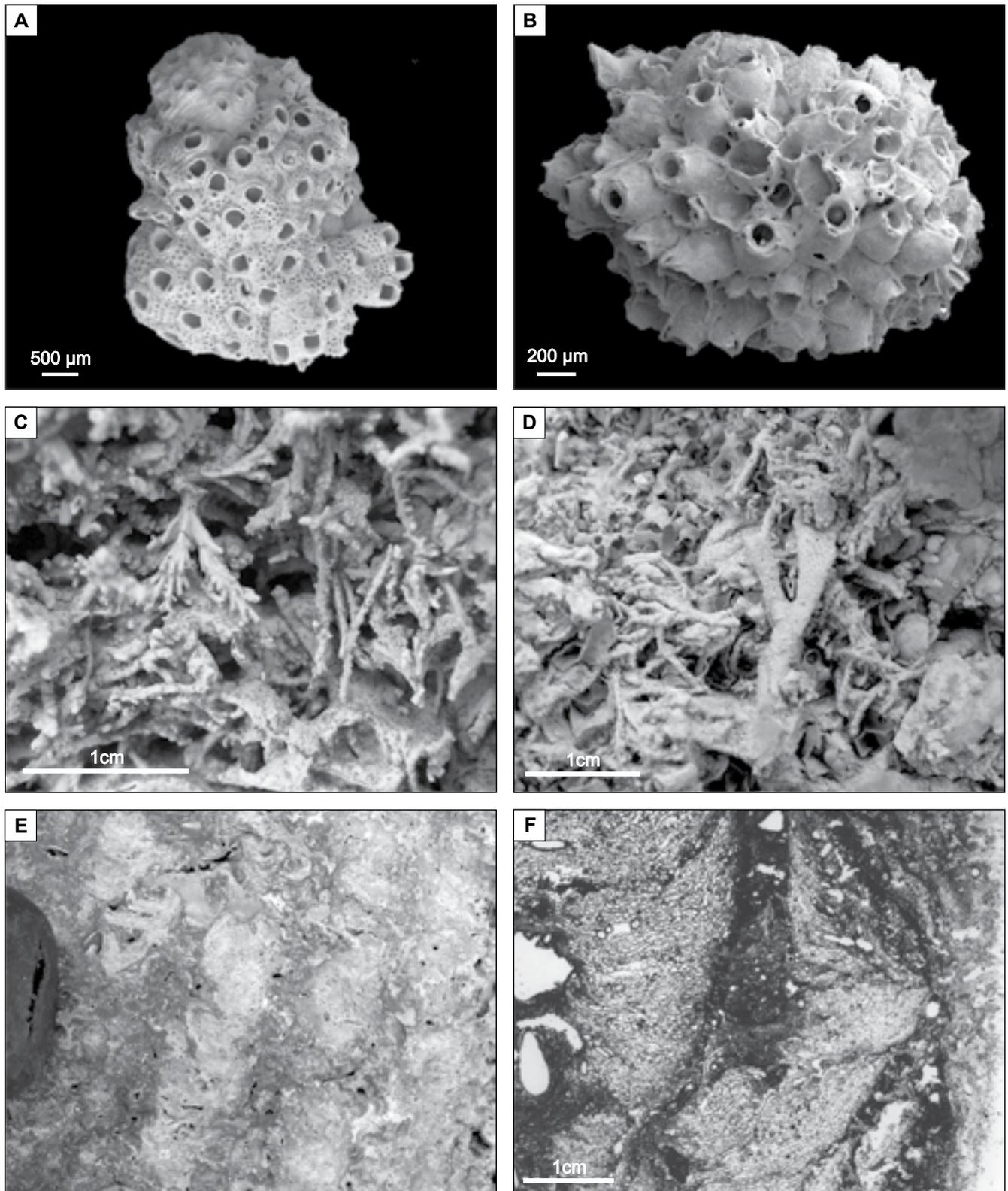
Fig. 14. Lower Sarmatian bryozoans from the serpulid-microbialite reefs

A − *Cryptosula terebrata* (Sinzov) overgrowing a tubuliporinid colony, Polupanivka; **B** − small colony of *Celleporina rostrata* (Małecki), Polupanivka; **C** − association of branching, cyclostome colonies, differently orientated, enclosed in a small cavern in the Sarmatian reef, Humentsi; **D** − association of branching and encrusting colonies in a cavern of reef-complex, Polupanivka; **E**, **F** − multilamellar colonies of *Schizoporella tetragona* Reuss, macro- (E) and thin section microphoto (F), Novosilka

to cope with (see Hageman *et al*., 2003).

Another characteristic abundant element of the Sarmatian reefs is *Cryptosula terebrata* (Sinzov), which is an ubiquitous and facies-independent species, forming either encrusting or branched colonies and found in marly, bioclastic and organodetritic limestones. *Celleporina rostrata* (Małecki) is a very common dweller of the Sarmatian reefs, which has been documented from marly and silty facies in the Polupanivka and Ditkivtsy quarries. It forms a globstone type of colonies ranging from 2 mm up to 1 cm in diameter.

The most common are tupuliporinids reperesented by *Tubulipora flabellaris* (Fabricius) and *T. dimidiata* (Reuss).

Branching cyclostomes are represented by small, finger-shaped colonies of *Crisia* Lamx, *Anguisia* Jullien, *Tervia* Jullien, *Entalophoroecia* Hermelin, *Ybselosoecia* Canu *et* Lecointre and unidentified tubuliporine cyclostomes (Taylor *et al.,* 2006).

Gastropods
(Figs. 15, 20C–E)

Among Late Badenian free-living reef-dwellers, one of the most abundant group are gastropods. Their assemblage is dominated by taxa typical for high-energy, rocky environments. The most characteristic and abundant is abalone species *Haliotis tuberculata* Linnaeus (see Fig. 7A). Although its ubiquity resulted in designation of the "*Haliotis* limestones" in the 19th century, it nowhere outnumbers the vermetid genus *Petaloconchus* H. Lea *et* C. Lea. At least two *Petaloconchus* species characterized by an extremely irregular growth of the shell are represented in Medobory. They were significant in the role of frame builders, so far the oldest known (*see* Vescogni *et al*., 2008).

Other common elements are representatives of the genus *Diodora* Gray and large, thick-shelled taxa belonging to the families Cypraeidae (cowries), Conidae, Strombidae and Turbinidae. Unfortunately, their state of preservation (moulds and imprints in massive coralline algae boundstone) in most cases highly impedes further taxonomic designation.

An abundance of gastropod shells is also typical of some lithofacies of the Lower Sarmatian reefal build-ups. In contrast to the Late Badenian, their assemblage, although sometimes rich in specimens, is relatively impoverished in taxa. The gastropods are small and usually thin-shelled and represented by the genera *Mohrensternia* Stoliczka, *Calliostoma* Swainson and *Bolma* Risso; specimens of *Cerithium* sp. are also common.

Bivalves
(Figs. 16, 17C–F, 18, 19, 20A, B, E)

Bivalves are the dominant organisms within reef-dwellers: 58 bivalve species representing 43 genera belonging to 24 families have been recognized in the Ukrainian part of Medobory, and 46 species representing 34 genera of 19 families in Moldova (see Studencka, Jasionowski, 2011). Unfortunately, their aragonitic shells are rarely preserved.

Only bivalve genera of the subclass Pteriomorphia such as *Manupecten* Monterosato, *Talochlamys* Iredale, *Aequipecten* Fischer, *Neopycnodonte* Stenzel and *Lima* Bruguière, having calcitic shells, are well preserved.

Because of the ongoing mining operations in the quarries, no quantitative analyses were performed. However, field observations have shown that three bivalve associations may be recognized in terms of species composition.

The most diverse and commonest within the Upper Badenian reefs is the *Chama* (*Psilopus*) *gryphoides–Lima* (*Lima*) *lima* association. Usually, 6 to 8 species are present, although as many as twelve may occur. *Chama* (*Psilopus*) *gryphoides* Linnaeus*,* a species cementing to the substrate, and the byssally attached *Lima* (*Lima*) *lima* (Linnaeus) are conspicuous elements. Scattered specimens of *Acar clathrata* (Defrance)*, Barbatia* (*Barbatia*) *barbata* (Linnaeus)*, Striarca lactea* (Linnaeus), *Spondylus* (*Spondylu*) *gaederopus* Linnaeus and *Venus* (*Ventricoloidea*) *libella* (Rayneval, Hecke *et* Ponzi) contribute to this association. Pectinids are only a subordinate element.

The *Neopycnodonte navicularis* association is represented by the oyster species forming dense overgrowths, which is the primary frame builder of the oyster build-ups that developed in the upper part of the coralline algae-vermetid reefs (see Figs 7E, 16C).

In the uppermost part of the reefs, the bivalve association is dominated by *Lithophaga* Röding, *Gastrochaena* Spengler and *Jouannetia* DesMoulins – genera typical of high-energy, rocky environments (see Fig. 17C–F). The population density of the rock-boring bivalve genus *Lithophaga* was very high, but its specific identification was possible only in very few cases of *Lithophaga* casts and shell remains. Some of them, bearing characteristic cross-striae, can be determined as *Lithophaga antillorum* (d'Orbigny). The other boring bivalves, *Gastrochaena* sp. and *Jouannetia* (*Jouannetia*) *semicaudata* DesMoulins, are less common. Borings of this latter are also commonly found in coral colonies in the Maksimivka quarry (Radwański *et al.*, 2006). The scavenger gastropod *Diodora* Gray was an important element of this association. The *Lithophaga* habitat was an important biotope for numerous marine species, including the bivalve *Kellia suborbicularis* (Montagu) and *Coralliophaga* (*Coralliophaga*) *lithophagella* (Lamarck)*,* which lived inside empty shells of *Lithophaga* (see Fig. 16D).

At the end of the Badenian, connection with the open sea was strongly restricted which caused a drastic change in environmental factors and resulted in significantly impoverished molluscan assemblages (Fig. 18). Out of 116 species that inhabited the Late Badenian reefs (in both the Medobory and Roztocze areas; after Studencka, 1994; Studencka, Jasionowski, 2011), only three species viz., *Mytilaster volhynicus* (Eichwald), *Crassostrea gryphoides* (Schlotheim) and *Obsoletiforma vindobonensis* (Laskarew) are known to have survived into the Sarmatian.

The Sarmatian serpulid-microbialite reefs that originated in ecologically extremely stressed environments related to mesohaline salinity, elevated alkalinity and eutrophic conditions, hosted twelve bivalve species, grouped in four associa-
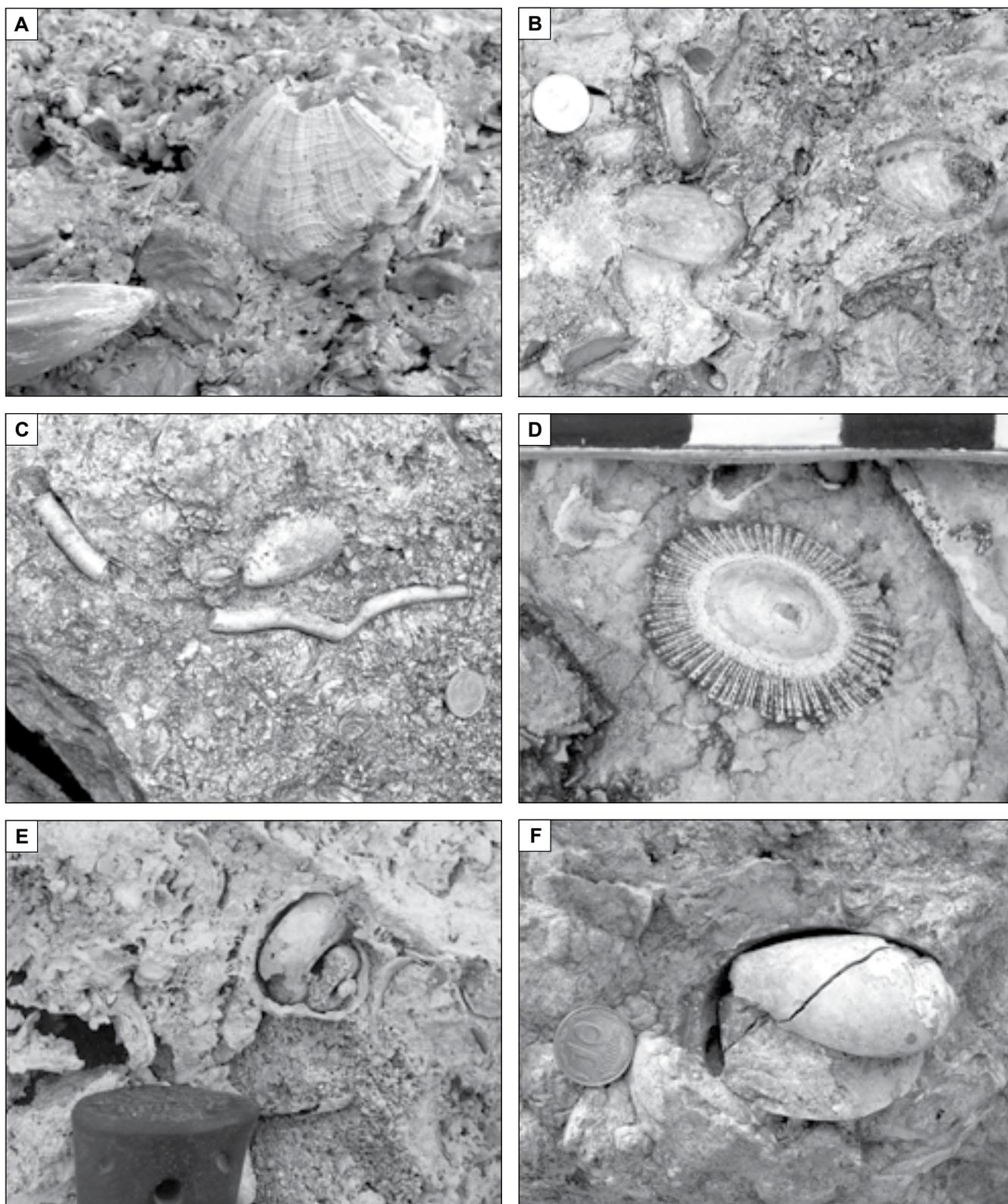
Fig. 15 Typical gastropods of the Upper Badenian reef facies of Medobory

A – abalone species *Haliotis tuberculata* Linnaeus with partly preserved aragonitic shell, Hai Roztotski; **B** – mass-occurrence of abalone shells, "*Haliotis* limestone", Maksymivka; **C** – mould of large vermetid gastropod, Maksymivka; **D** – limpet gastropod *Diodora* sp., Hai Roztotski; **E** – mould of *Bolma mamillaris* (Eichwald), Maksymivka; **F** – mould of large cowry (Cypraeidae), Hai Roztotski
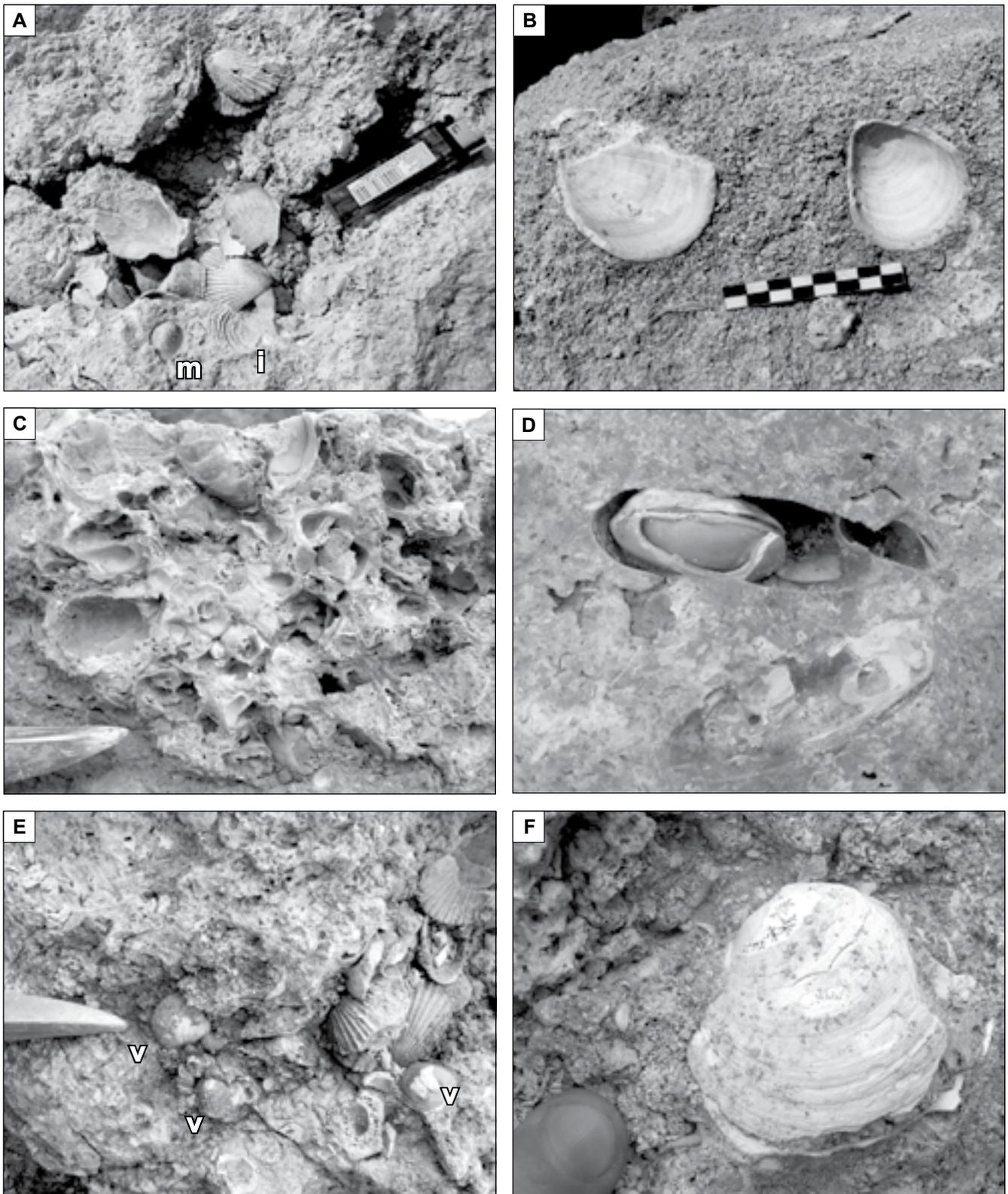
Fig. 16. Typical (non-boring) bivalves of the Upper Badenian reef facies of Medobory

A – mass-occurrence of shells attributed to scallop *Talochlamys multistriata* (Poli), imprint (i) and mould (m) of *Chama* (*Psilopus*) *gryphoides* Linnaeus is also visible, Nihyn; **B** – shells of *Spondylus* sp. in coarse calcarenite, Hai Roztotski; **C** – mass-occurrence of oysters *Neopycnodonte navicularis* (Brocchi), Hai Roztotski; **D** – presumed *Coralliophaga* sp. specimen preserved in boring of *Lithophaga* sp., Haluschyntsi; **E** – surprisingly well-preserved aragonitic shells (v) of *Venus* (*Ventricoloidea*) *libella* (Rayneval, Hecke *et* Ponzi) accompanied by fragmented shells of scallop *Aequipecten macrotis* (Sowerby), Maksymivka; **F** – well-preserved aragonitic shell of *Pelecyora* sp., most probably *P.* (*Cordiopsis*) *gigas* (Lamarck) in coarse calcarenite, Hai Roztotski
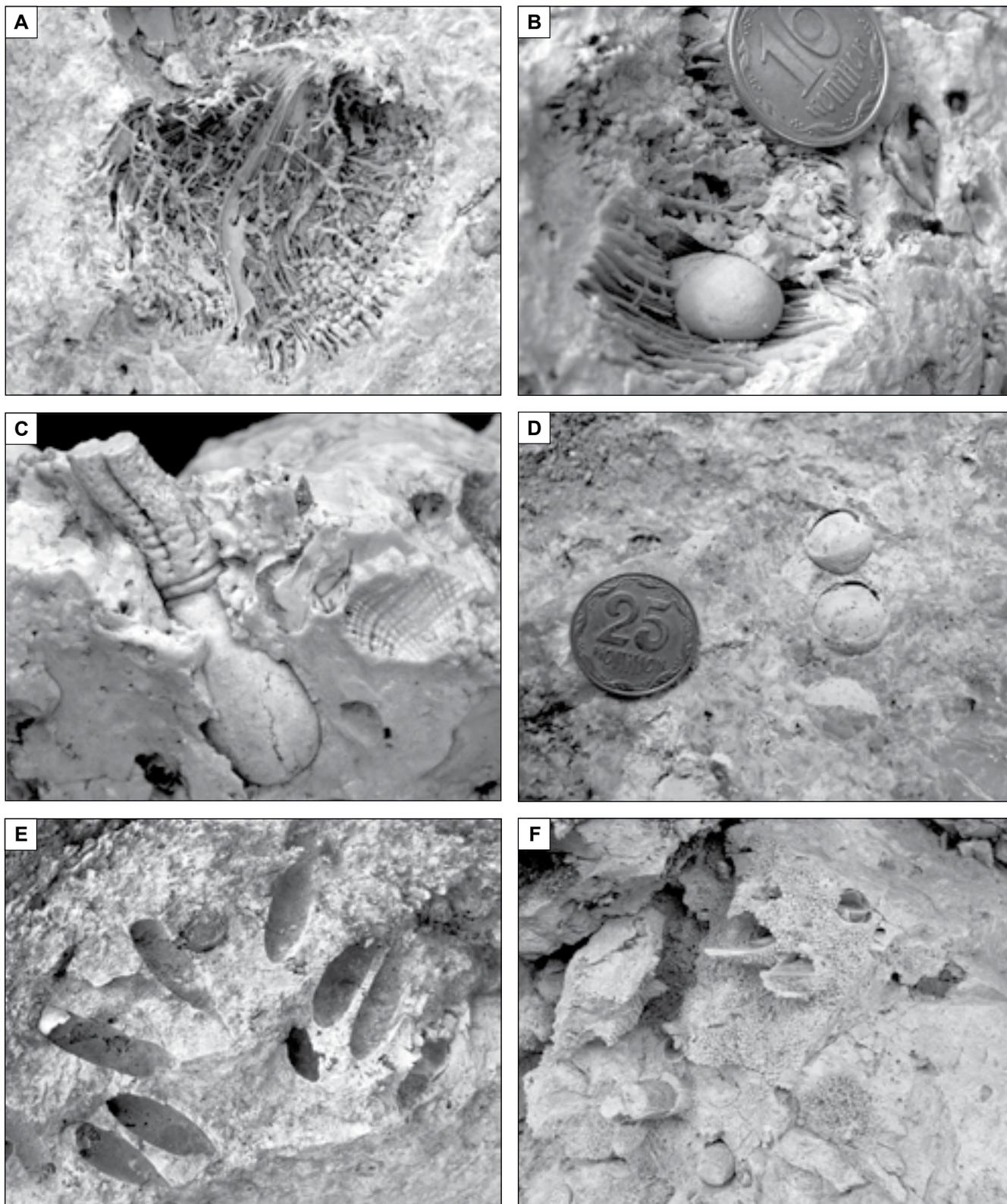
Fig. 17. Boring organisms of the Upper Badenian reef facies of Medobory

A – *Entobia* ichnosp., moulds ("*Entobia* balls") of chambers bored by clionid sponges in bivalve shell (dissolved), Haluschyntsi; B – "*Entobia* balls" and a mould of *Gastrochaena* sp. boring, Maksymivka; C – well-preserved mould of *Gastrochaena* sp. in its boring (*Gastrochaenolites* ichnosp.) in coralline-algae boundstone, Zbarazh; D – moulds of *Jouannetia semicaudata* DesMoulins in bored coralline algae boundstone, Haluschyntsi; E – mass-occurring borings of *Lithophaga* sp. in coralline algae boundstone, Nihyn; F – mass-occurring borings of *Lithophaga* sp. (some with geopetal micritic infilling) in colony of *Tarbellastraea reussiana* (Milne-Edwards *et* Haime), Demkivtsi
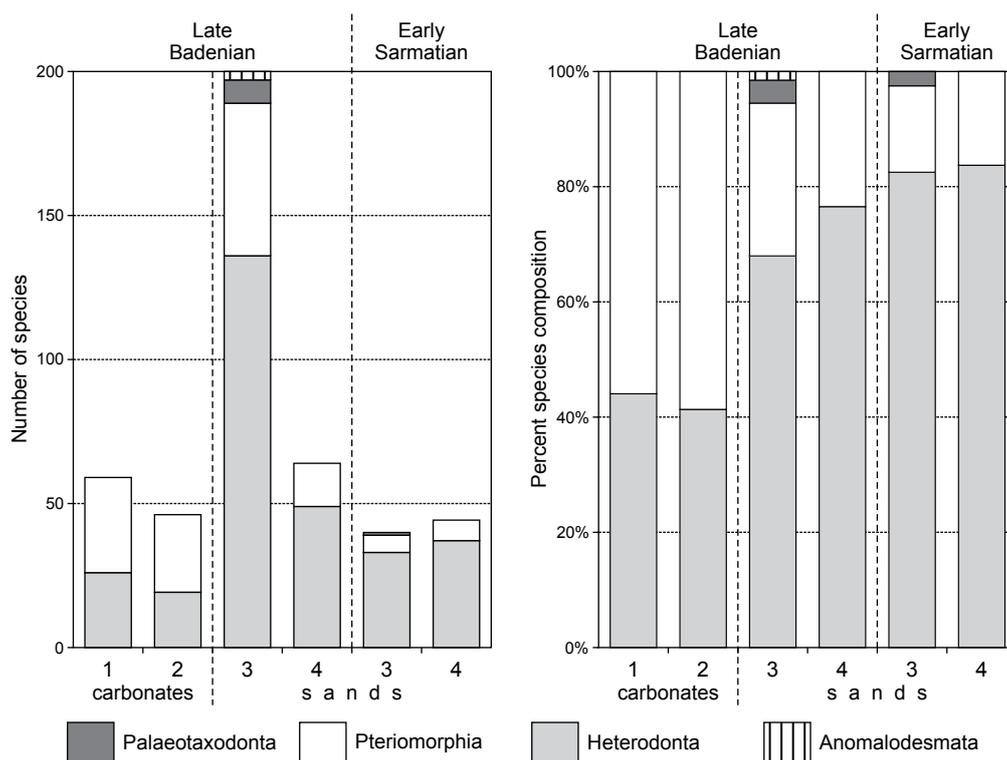
Fig. 18. Percentages of major taxonomic bivalve groups and number of species recorded in the Upper Badenian Medobory reefs, and those derived from the Upper Badenian and Lower Sarmatian sandy facies (after Studencka, Jasionowski, 2011; modified)

The diversity of bivalves that inhabited areas adjoining the Medobory reefs was reduced due to environment changes around the Badenian/Sarmatian boundary, albeit not as severely as in Medobory. Abbreviations: 1 – Medobory reefs, Ukraine; 2 – Medobory reefs, Moldova; 3 – Podolian area, Ukraine; 4 – Moldova

tions: the *Crassostrea gryphoides*, *Obsoletiforma volhynica–Mytilaster volhynicus*, *Obsoletiforma sarmatica* and *Obsoletiforma volhynica–Musculus sarmaticus* associations. The most noticeable difference between the Badenian and Sarmatian bivalves is the complete lack of marine stenohaline taxa in the Sarmatian reefs and the abundance and ubiquity of representatives of the genus *Obsoletiforma* Paramonova. Five species were recognized, three of which being common.

The Parathethyan endemic bivalve genus *Obsoletiforma* Paramonova is inferred to spring from the genus *Cerastoderma* Poli. It is highly likely that, similarly to modern representatives of *Cerastoderma edule* (Linnaeus), it colonized nearshore muddy gravel.

In Medobory, *Obsoletiforma lithopodolica* (du Bois) and *Obsoletiforma sarmatica* (Kolesnikov) commonly occur in a serpulid (or bryozoan) microbialite boundstone, the dominant facies of reefs. Locally these cockles are ubiquitous and formed oligotypic accumulations. *Obsoletiforma volhynica* (Grischkevitsch) is largely restricted to the serpulid-microbialite frame consisting of superimposed bunches of semi-parallel serpulid tubes covered with microbialitic crusts. Massive accumulations of serpulid tubes typically occur in environments of high ecological stress that are inhospitable to other biota. Hence, the abundance and ubiquity of this cockle species together with densely clotted serpulid colonies clearly illustrate that the species was fully adapted to

life in extremely stressed environments.

Sponges
(Fig. 17A, B)

Sponges are present in the Late Badenian reefs only. These are just traces (*Entobia* ichnosp.) of boring clionid sponges referred to as *Cliona vastifica* Hancock and *Cliona celata* Grant. The traces, although sometimes may be observed as a system of chambers in bivalve shells, are most often preserved as calcitic fills ("*Entobia* balls"; see Radwański *et al.*, 2011) due to dissolution of originally aragonitic shells.

Crustaceans
(Fig. 21A–E)

The remains of crustaceans are a quite common component of Late Badenian reefal facies (not recorded in Early Sarmatian deposits) as they occur especially in detrital sediment that fills growth cavities and tiered canals interpreted as burrows of *Alpheus* sp. within the reef boundstone. The occurrence of these burrows indicates extremely shallow littoral environment (Radwański *et al.*, 2006), but also makes it possible to find specimens of fauna with more delicate skeletons.

Almost all recorded taxa represent crabs *sensu stricto*,
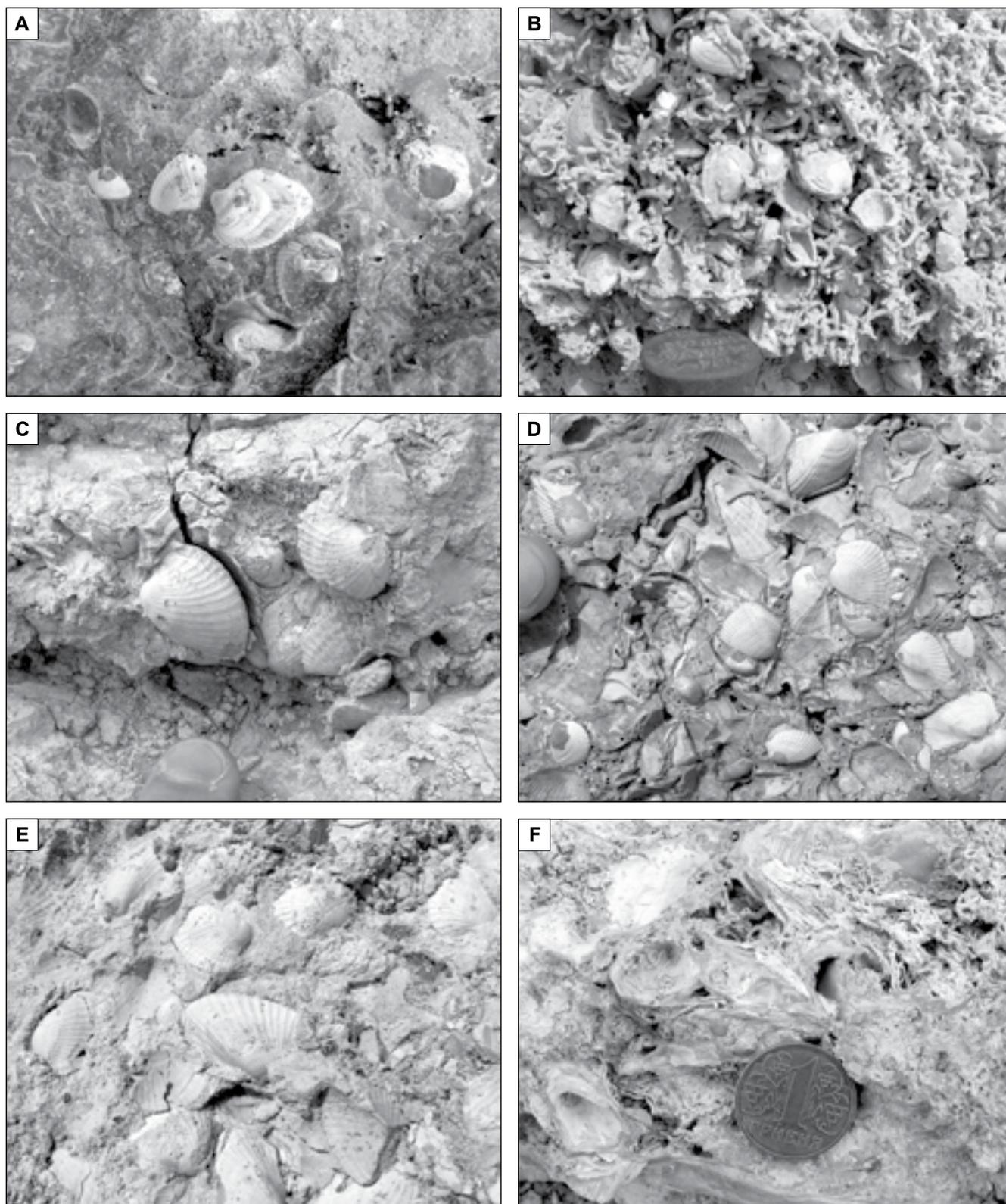
Fig. 19. Typical bivalves of the Lower Sarmatian reef facies of Medobory

A – shell of *Obsoletiforma lithopodolica* (du Bois) in microbialite boundstone, Ditkivtsi; **B** – shells of *Obsoletiforma volhynica* (Grischkevitsch), surrounded by serpulid tubes, Vikno; **C** – articulated shells of *Obsoletiforma lithopodolica* (du Bois), Nihyn; **D** – shells of *Obsoletiforma volhynica* (Grischkevitsch) from serpulid-mibrobialite limestones, Vikno; **E** – oligotypic accumulation of giant shell of *Obsoletiforma sarmatica* (Kolesnikov), Humentsi; **F** – small cluster of *Crassostrea gryphoides* (Schlotheim) shells associated with serpulids, Humentsi
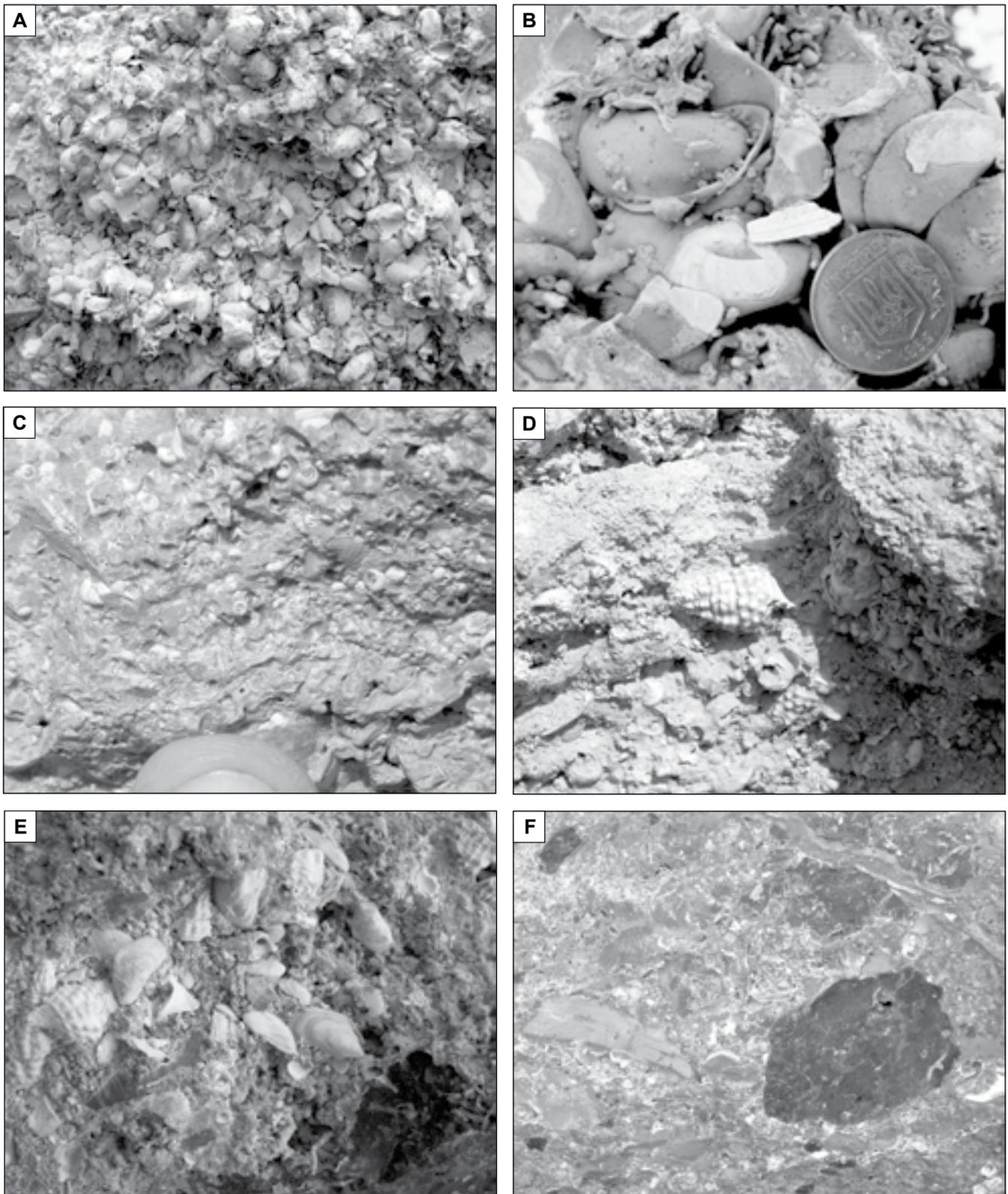
Fig. 20. Typical bivalves and gastropods of the Lower Sarmatian reef facies of Medobory

A – oligotypic accumulation of *Musculus sarmaticus* (Gatuev) shells, Zakupne; **B** – shells of *Musculus sarmaticus* (Gatuev) surrounded by serpulid tubes, Vikno; **C** – mass occurrence of small-size gastropods tentatively identified to the genus *Gibbula* Risso, Vikno; **D** – cerithid shells found in poorly sorted clastic material, Humentsi; **E** – aragonitic shells of *Mytilaster volhynicus* (Eichwald) and cerithids with black pebbles, Novosilka; **F** – synsedimentary reef breccia composed of clasts of various Sarmatian rocks including numerous black pebbles, Ditkivtsi
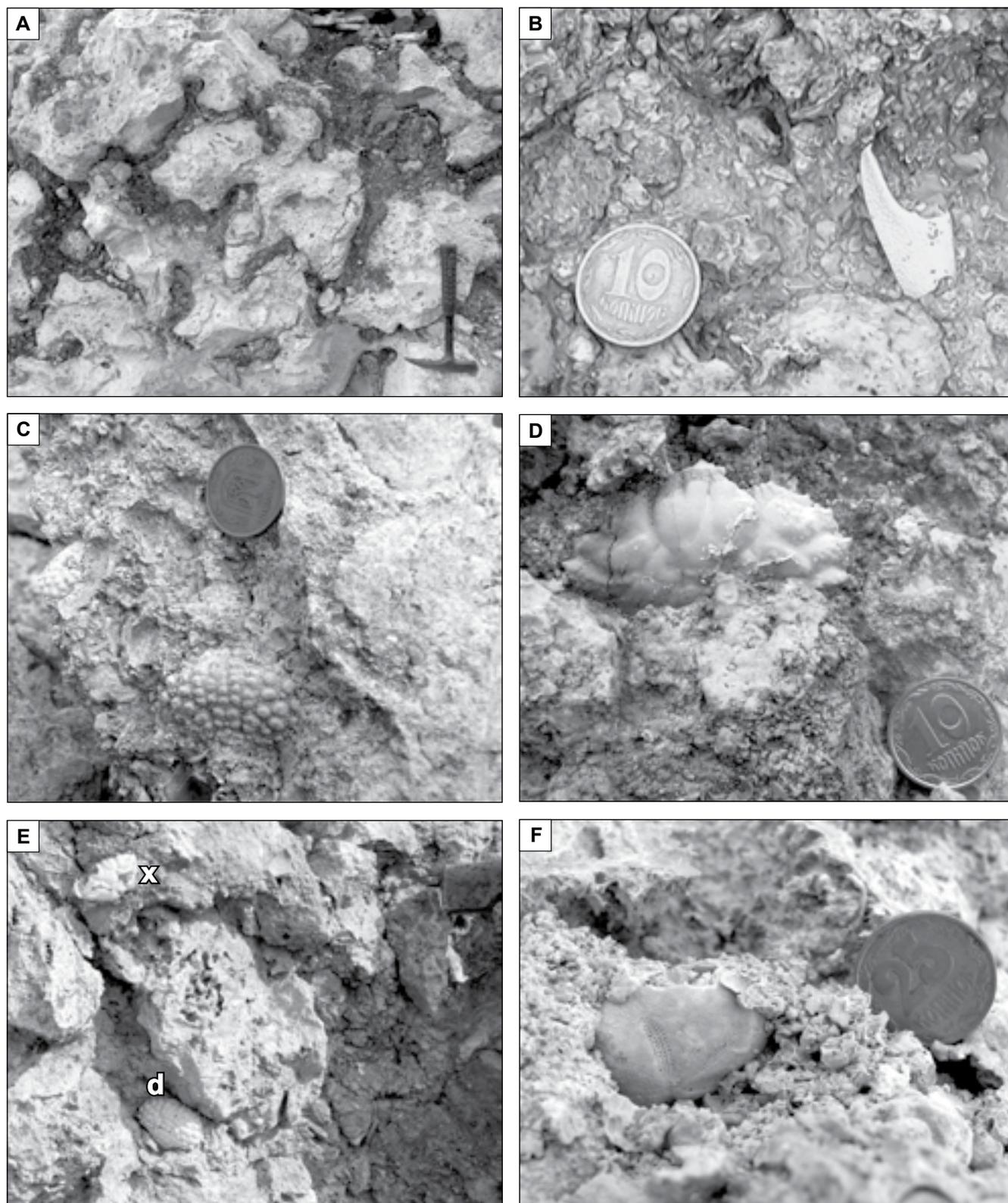
Fig. 21. Additional fauna of the Upper Badenian reefal facies of Medobory

A – system of burrows attributable to alpheid shrimp *Alpheus* sp., Sakhkamin; **B** – propodus of crab *Petrolisthes magnus* Müller, Sakhkamin; **C** – carapace of crab *Daira speciosa* (Reuss), Sakhkamin; **D** – carapace of crab *Xantho moldavicus* (Janakevich), Maksymivka; **E** – co-occurring specimens (carapaces) of *Daira speciosa* (d) and *Xantho moldavicus* (x), Haluschyntsi; **F** – slightly damaged test of juvenile specimen of brissid spatangoid *Brissus unicolor* (Leske), Nihyn

only *Galathea weinfurteri* Bachmayer is a squat lobster, and the supposed *Alpheus* is a shrimp (Radwański *et al.*, 2006). The assemblage of crabs is composed of three abundant taxa: *Petrolisthes magnus* Müller, *Daira speciosa* (Reuss) and *Xantho moldavicus* (Janakevich), while much less frequent are: *Petrolisthes magnus* Müller, *Petrolisthes haydni* Müller, *Chlorodiella tetenyensis mediterranea* Müller and *Pilumnus mediterraneus* (Lőrenthey). Crustacean taxa are typical of reefal communities (*see* Müller, 1984; Karasawa, 2000) and they are also very commonly observed in other Tethyan and Paratethyan localities (Müller 1984, 1996). Moreover, most of the discussed genera are also typical of the present-day tropical/subtropical Indo-Pacific bioprovince (see Janakevich, 1969; Förster, 1979; Müller, 1979).

Echinoderms
(Fig. 21F)

Echinoderms are represented in the investigated deposits by echinoids. Their assemblage from Medobory, well represented within the Late Badenian coralgal build-ups, differs markedly from other echinoid assemblages known from the Middle Miocene (Badenian) of the Polish and Ukrainian parts of the Carpathian Foredeep Basin (Radwański, Wysocka, 2004; Kroh, 2005, and Szörényi, 1953; Radwański, Wysocka, 2001, respectively). The assemblage is composed almost solely of cidaroids and brissid spatangoids. Among cidaroids, the species *Eucidaris zeamays* (Sismonda) is relatively common; its test fragments were noticed also in detrital facies. It is noteworthy that the present-day representatives of this genus live among littoral rubble and/or coral crevices where they hide during daytime. Brissid spatangoids are represented by the extant cosmopolitan species *Brissus unicolor* (Leske), which is known from various warm-temperate to subtropical/tropical habitats. Although rare, it is particularly characteristic of the Caribbean eastern Atlantic, and the Mediterranean. It lives usually buried in sand, although in the Caribbean it was also noticed in sand-

filled hollows in reefal build-ups (Radwański *et al.*, 2006). No representatives of echinoderms were noticed in the Sarmatian of the investigated area.

CONDITIONS OF REEF DEVELOPMENT

The Middle Miocene was a period of most rapid development of reefs during the Cenozoic (Perrin, 2002). This refers in particular to the Mediterranean area and to the more northerly located Parathetys where, in the Badenian, reefal build-ups quite commonly occurred usually as relatively small patchy reefs with coralline-algae being the main rock-building organisms (Pisera, 1985, 1996; Studencki 1988a, b, 1999).

Among all known Paratethyan reefs, these from Medobory have the largest dimensions (Fig. 22). Relatively small abundance of corals was probably due to the location of the region outside the tropical belt. Coralline-algae reefs of Medobory formed in shallow and relatively warm waters of open-marine salinity and high hydrodynamic energy. The presence of corals and other warm-water taxa in the Medobory reefs suggests that the water in which they formed, were slightly warmer than those of Roztocze in Poland. In contrast, in more southward located areas of present-day Hunga-
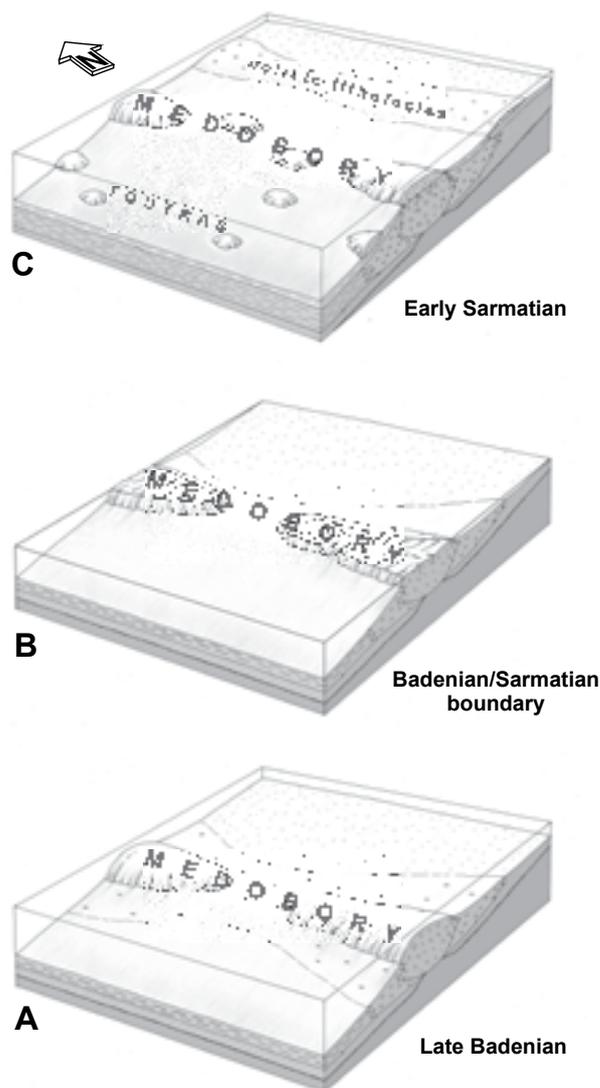
Fig. 22. Supposed restoration of the Medobory area in Late Badenian–Early Sarmatian time

A – Late Badenian: development of a reef belt (barrier reef) caused gradual limitation of open-marine conditions in the back-reef (lagoonal) area; **B** – Badenian/Sarmatian boundary: tectonically-controlled emersion caused intense weathering/karstification of Upper Badenian reef deposits and development of restricted conditions in a lagoonal area; **C** – Early Sarmatian: development of a new generation of reefs above the previously existing Upper Badenian limestones, isolated toutras appear commonly in fore-reef and back-reef areas. Within a lagoon, the formation of oolitic lithofacies takes place

ry and Bulgaria, corals play an important role as a reef-builder. Thus, it confirms the significance of water temperature (related to geographical latitude) for relative abundance of hermatypic corals. Little taxonomic diversity of corals and the presence of genus *Porites* Link suggest relatively fertile waters and a considerable supply of suspended terrigenous material, most probably from back-reef (lagoonal) areas (see McCall *et al.,* 1994).

The connection between the Paratethys and Mediterranean was interrupted since the latest Badenian and the Paratethys became a mixo-mesohaline (semi-marine) basin. Development of the Early Sarmatian serpulid-microbialite reefs was caused by specific environmental conditions prevailing during that time in the Paratethys. As a result of isolation of the Paratethys, a unique mixture of taxonomically impoverished fauna (only a few opportunistic groups of invertebrates) and microbial mats developed; the latter, due to favourable water chemistry (strong relative supersaturation of calcium carbonate), were synsedimentarily calcified. Massive occurrences of these opportunistic taxa resulted in development of large organic build-ups. This process was accelerated by supersaturation of $CaCO_3$, which was locally common in shallow, restricted coastal areas, and caused by intense evaporation of decreasing water salinity.

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