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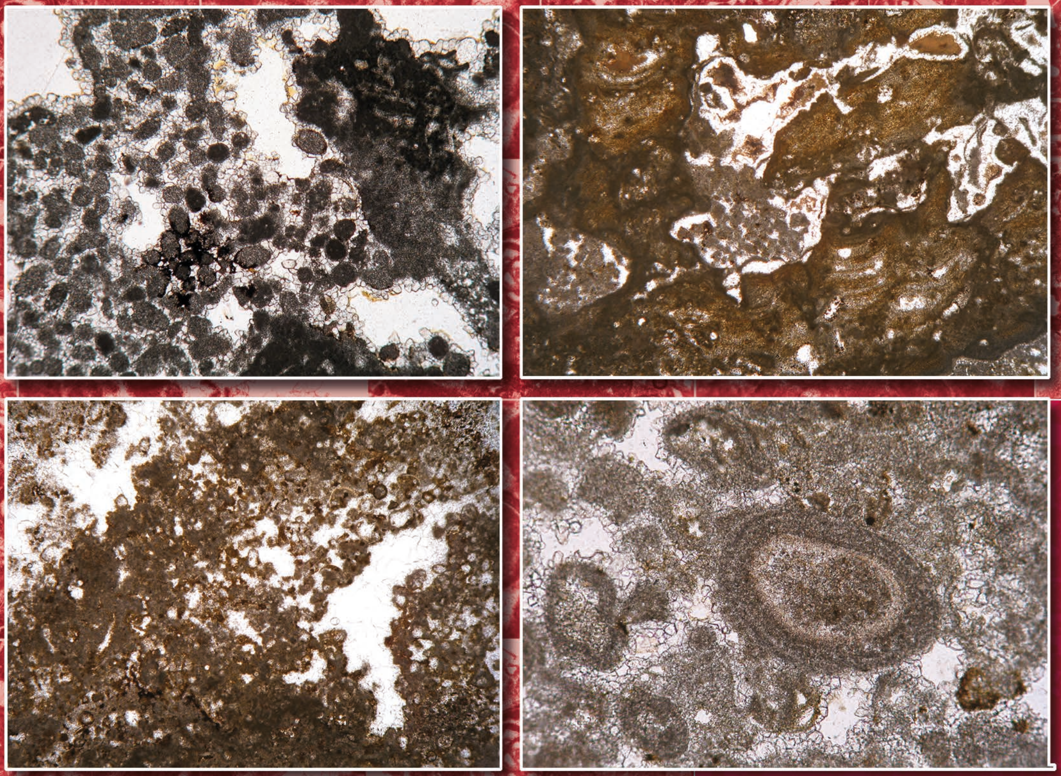

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# The Sarmatian (middle Miocene) "petrified forest" of Gramada (NW Bulgaria): role of the calcareous crusts

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## ABSTRACT

The Sarmatian (upper Serravallian, middle Miocene) layers cropping out at Gramada (North-West Bulgaria) contain calcareous cylinders of metric dimensions characterized by a central and cavity also cylindrical. Their detailed study shows both vertical and concentric structuring features. The various component elements of the cylinders result from sequences of micritic carbonate crusts with several components, mostly of algal origin (red algae) and to a lesser extent of microbial origin. Besides few ostracods, the lack of associated fauna is a peculiar feature that raises the issue of the depositional environment, in the context of the evolution of the Sarmatian sedimentation at the scale of the Paratethys area. The encrustation processes around possible vegetal supports ("petrified forest") are also discussed.

KEY WORDS
Bulgaria,
Miocene,
Sarmatian,
"petrified forest",
calcareous crusts,
Paratethys.

## RÉSUMÉ

*La « forêt pétrifiée » sarmatienne (Miocène moyen) de Gramada (nord-ouest de la Bulgarie) : le rôle d'une succession d'encroûtements calcaires.*

Les couches du Sarmatien (Serravallien supérieur, Miocène moyen) affleurant à Gramada (Nord-Ouest de la Bulgarie) renferment des cylindres calcaires de dimensions métriques caractérisés par une cavité centrale également cylindrique. Leur étude détaillée montre une structuration à la fois verticale et concentrique. Les différents éléments constitutifs des cylindres résultent de séquences d'encroûtements carbonatés micritiques à plusieurs composants en majorité d'origine algaire (corallinacées) et dans une moindre mesure microbienne. L'absence de faune associée, hormis les ostracodes, est une caractéristique particulière qui pose le problème de l'environnement de dépôt qui s'inscrit dans le cadre de l'évolution de la sédimentation sarmatienne dans l'ensemble de la Paratéthys. Le mode de formation autour d'éventuels supports végétaux (« forêt pétrifiée ») est également discuté.

MOTS CLÉS
Bulgarie,
Miocène,
Sarmatien,
« forêt pétrifiée »,
encroûtements calcaires,
Paratéthys.

## INTRODUCTION

Usually, geological sites qualified as "petrified forests" correspond to the preservation of fossilized tree trunks *in situ*, more or less in a living position. Much more rarely "petrified forests" are in fact characterized by cylinder-shaped calcareous crusts of various thickness, developped around a disappeared vegetal substrate leaving a central cavity also cylindrical (Timpe 2010). Due to the great number of cylinders and their large size, these sites are spectacular aspect. Some of them has led to be listed as areas of geoheritage interest. The best-known example is the Lulworth Cove fossil forest (Dorset, England) dating from the Late Jurassic (Gallois *et al.* 2018). Other noteworthy sites have been recorded in Miocene formations. This is the case of the "petrified forest" from the Perfugas-Martis Carrucana area in Sardinia (Italy) of Burdigalian age (Sowerbuts 2000; Timpe 2010; Zoboli & Pillola 2017; personal observations). This is also the case of the Sarmatian site of Gramada (upper Serravallian, middle Miocene, Bulgaria) which displays numerous cylindrical calcareous structures exhibiting a central tubular cavity, called "chuturites" because of the resemblance with a flask-shaped recipient used by the inhabitants of the region.

The Gramada geosite was included in the inventory of Bulgarian natural sites in 1968. Subsequently it was integrated into a European Interreg program (2007-2011) concerning the Bulgarian region of Vidin (European Union through the Cross-Border Programme 2021): "New informational technologies and tourism products for cross border tourism development". In spite of its web visibility, the Gramada geosite remains very little known and does not benefit from scientific interest commensurate with its originality and spectacular appearance (Sinyovski 2003, 2009). The aim of this work is therefore to provide precise data on the nature of these calcareous structures and to try to understand their formation processes in the framework of the Sarmatian sedimentary events in Paratethys.

## GEOGRAPHICAL AND GEOLOGICAL FRAMEWORK

The Gramada geosite area is located in the extreme northwest of Bulgaria in the province of Vidin, separated from Romania by the Danube (Fig. 1A). The field observations were made in the immediate vicinity to the north of the Gramada municipality located about fifteen kilometers southwest of the town of Vidin (Fig. 1B).

The hydrographic network allows the observation of Miocene lands mainly represented by layers of Sarmatian age (Fig. 2A). The stratigraphic subdivisions of the Sarmatian of North-West Bulgaria (Koleva-Rekalova 2000) successively include the Volhynian (lower Sarmatian), the Bessarabian (upper Sarmatian) and the Khersonian (late Sarmatian). According to the geological map of Vidin at 1: 100 000, these three stratigraphic units occur from bottom to top (Fig. 2A):

– the Dimovsk Formation (Volhynian-Bessarabian) composed of sands, sandstones and bioclastic limestones;

TABLE 1. — Dimensions of the cylinders in cm.

| | Diameter | | | | |
|---|---|---|---|---|---|
| Cylinders | at the base | at the center | at the top | of the central cavity | Total lenght |
| GR1 | 55 | 70 | 59 | 15 | 107 |
| GR2 | 52 | 76 | 53 | 16 | 128 |
| GR3 | 61 | 68 | 69 | 12 | 133 |
| GR4 | 65 | 75 | 83 | 11 | 135 |
| GR5 | 62 | 69 | 70 | 10 | 106 |
| GR6 | 67 | 70 | 70 | – | 81 |
| GR7 | 65 | 73 | 61 | 11 | 120 |
| GR8 | 59 | 66 | 63 | 16 | 109 |
| GR9 | 61 | 63 | 62 | – | 80 |
| GR10 | 71 | 82 | 74 | – | 101 |
| GR11 | 58 | 84 | 72 | 10 | 128 |
| GR12 | 88 | 101 | 104 | 16 | 100 |
| GR13 | 69 | 82 | 56 | – | 94 |
| GR14 | 62 | 66 | 53 | 9 | 112 |
| GR15 | 55 | 67 | 59 | 10 | 107 |
| GR16 | 50 | 68 | 64 | – | 85 |
| GR17 | 54 | 78 | 65 | – | 117 |
| GR18 | 56 | 82 | 83 | – | 104 |
| GR19 | 57 | 72 | 64 | – | 113 |
| GR20 | 55 | 57 | 62 | – | 85 |
| GR21 | 59 | 98 | 62 | 8 | 140 |
| GR22 | 63 | 77 | 56 | – | 103 |
| GR23 | 72 | 82 | 68 | 18 | 105 |
| GR24 | 71 | 82 | 67 | 15 | 138 |
| GR25 | 61 | 85 | 95 | 10 | 101 |
| GR26 | 64 | 82 | 53 | – | 125 |
| GR27 | 75 | 121 | 44 | 19 | 112 |
| GR28 | 56 | 83 | 64 | – | 111 |
| GR29 | 67 | 84 | 58 | – | 100 |
| GR30 | 44 | 66 | 89 | – | 95 |
| Means | 61.80 | 77.63 | 66.73 | 12.88 | 109.17 |

– the Krivodol Formation (Volhynian-Bessarabian) containing clays, clayey and sandy limestones and locally interspersed in the Dimovsk Formation;

– the Furen Formation (Bessarabian-Khersonian) composed of limestones with sandy-clay intercalations. The Bessarabian age was based on the presence of the following mollusk assemblage: *Mactra* (*Sarmatimactra*) *vitaliana fabreana* (Orbigny, 1845), *Plicatiforma fittoni fittoni* (Orbigny, 1845), *Obsoletiforma* (*Sarmaticardium*) *desperata* (Kolesnikov, 1929).

The calcareous cylinders of the Gramada geosite come from the upper part of the Furen Formation.

## MATERIAL AND METHODS

In order to assess the dimensions of Gramada cylinders and to best account for their more or less swollen shape, several measurements were carried out on the field on about thirty complete specimens, that correspond to extracted and moved ones. The following dimensions were therefore taken into account on the cylinders: total length, diameter at the base, diameter at the most bulging part, diameter at the top, measurable diameter of the cavity. These data are reported in Table 1.

In order to assess the density and the spatial distribution of the cylinders, an indicative position survey was carried out for around thirty specimens remained in place.


FIG. 1. — **A**, Geographical location of the study area in Bulgaria; **B**, Studied area in the Vidin district.

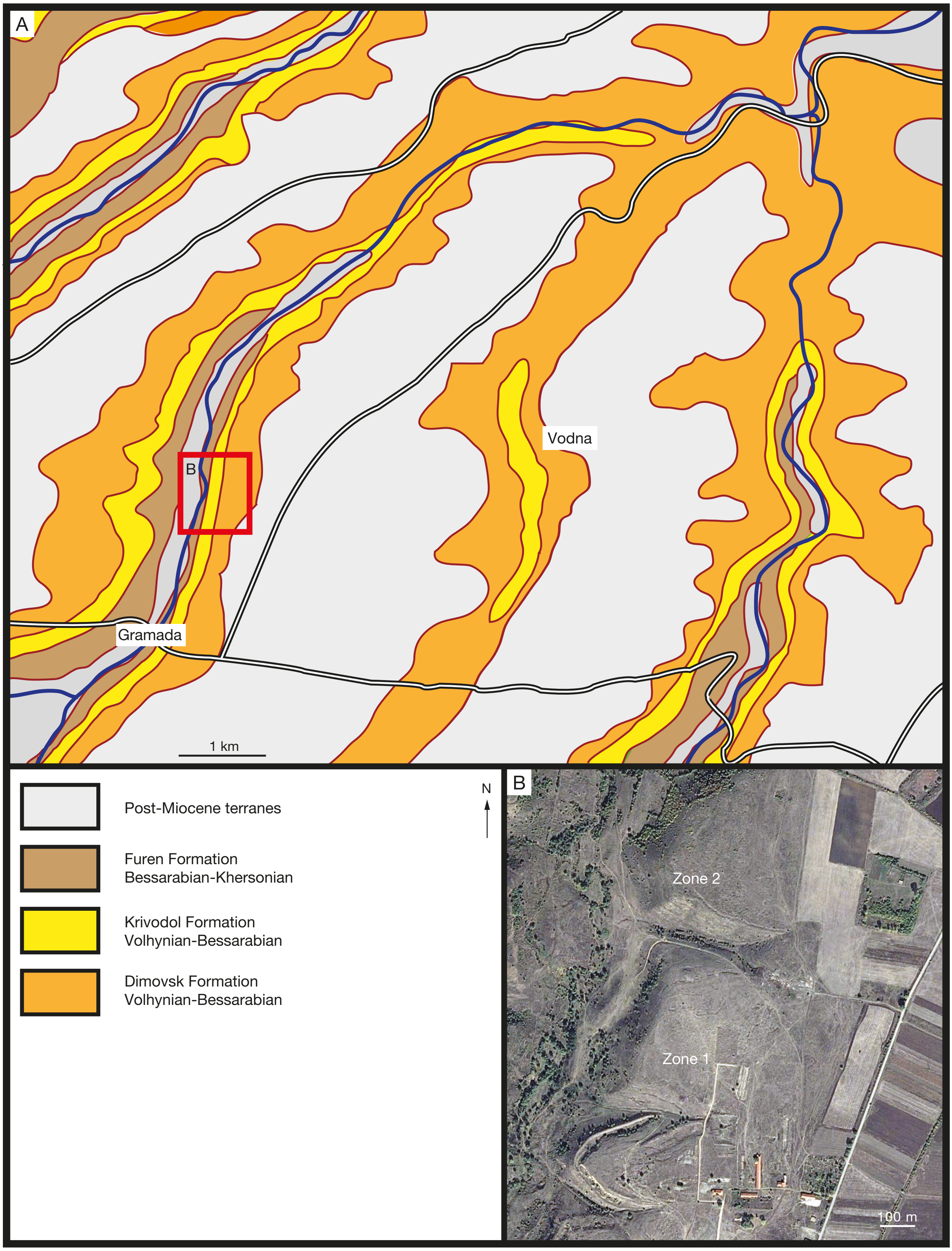


Fig. 2. — **A**, Geological map of the studied area; **B**, Satellite view of the outcrops to the north of the locality of Gramada and location of the two main zones exhibiting the calcareous cylinders.

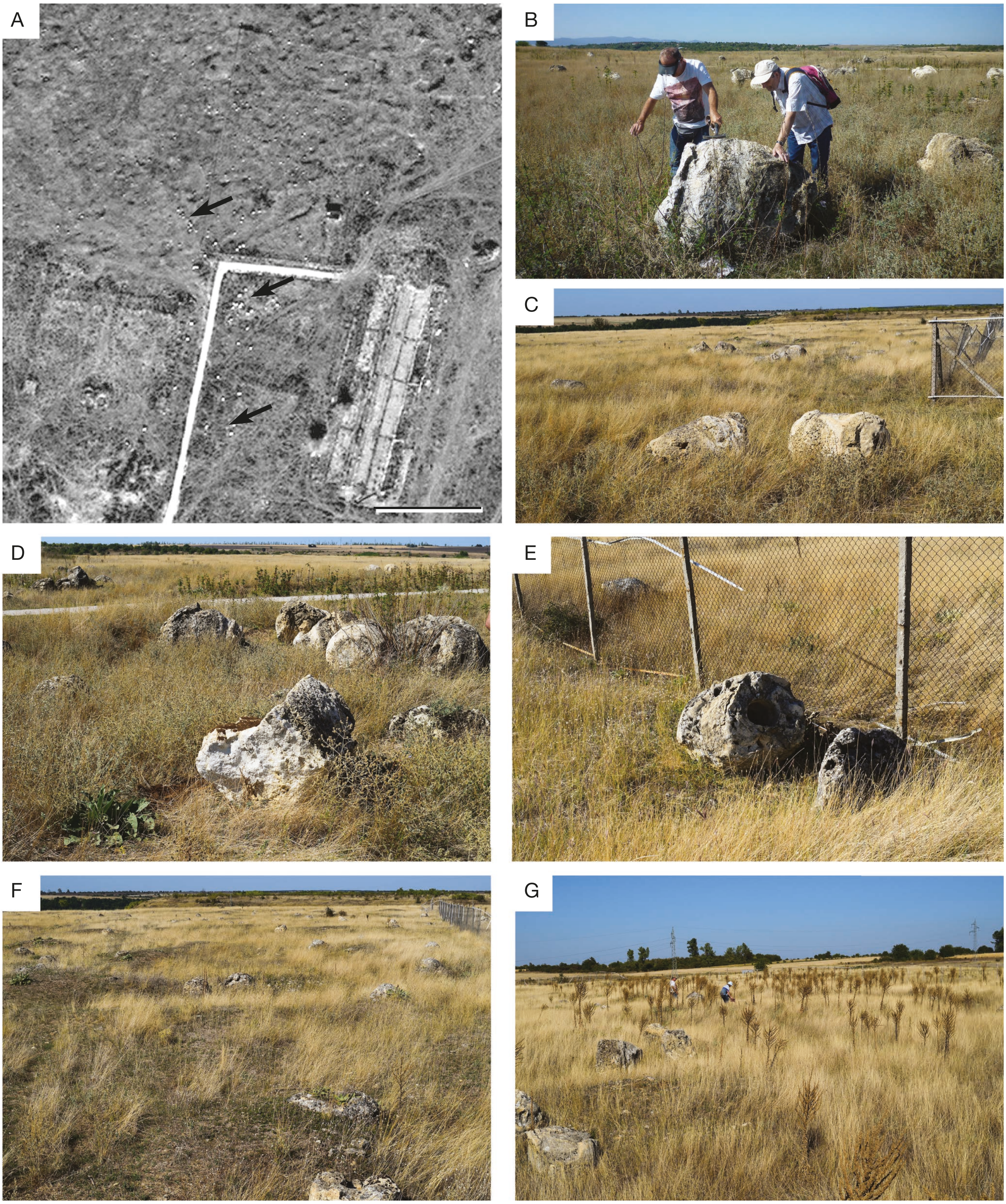


FIG. 3. — **A**, Satellite view of zone 1; the white dots represent the cylinders; **B**-**E**, Cylinders artificially displaced and horizontally arranged; **F**, **G**, Cylinders in vertical position, probably in their natural place. Scale bar: A, 50 m.

In order to perform sedimentological analyses, samples were taken from the different parts of the cylinders (see description below). The microfacies study is based on petrographic thin sections examined with a Zeiss Axioskop 40 polarizing microscope equipped with a Canon Powershot A photographic imaging system.

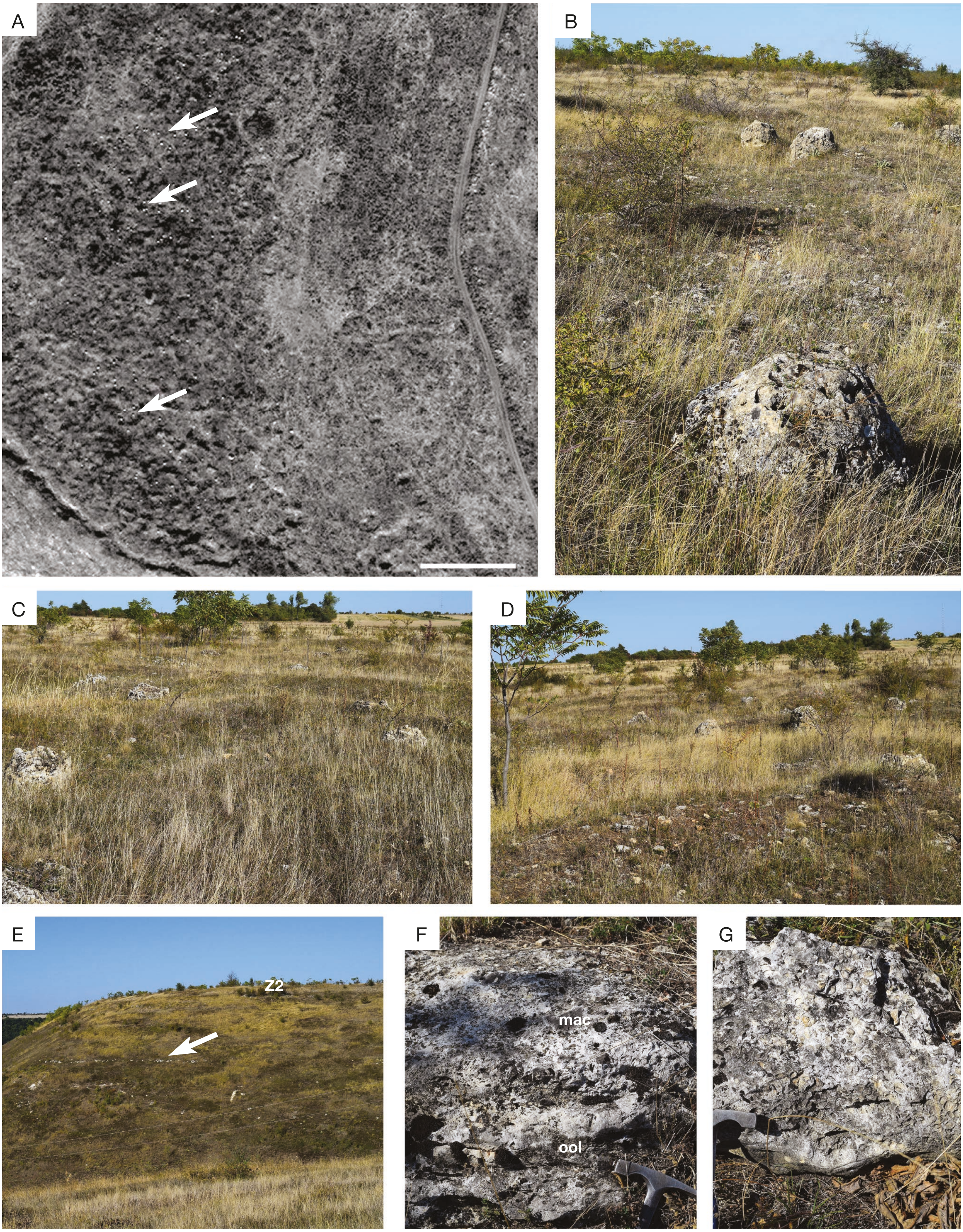


FIG. 4. — **A**, Satellite view of zone 2; the white dots represents the cylinders (the white arrows indicate the place of some cylinders); **B**-**D**, Cylinders in natural vertical position; **B**, Example of cylinder exhibiting a preserved dome shaped in form of "hat"; **E**, View of the outcrop under the zone 2 (Z2) with horizontal limestone beds indicated by the white arrow; **F**, Detail of the outcrops directly below the cylinder zone; it displays the oolitic limestone (**ool**) topped with *Mactra* limestone (**mac**); **G**, Detail of the limestone with accumulations of *Mactra*. Scale bar: A, 50 m; F, G, the hammer (length: 28 cm) gives the scale.

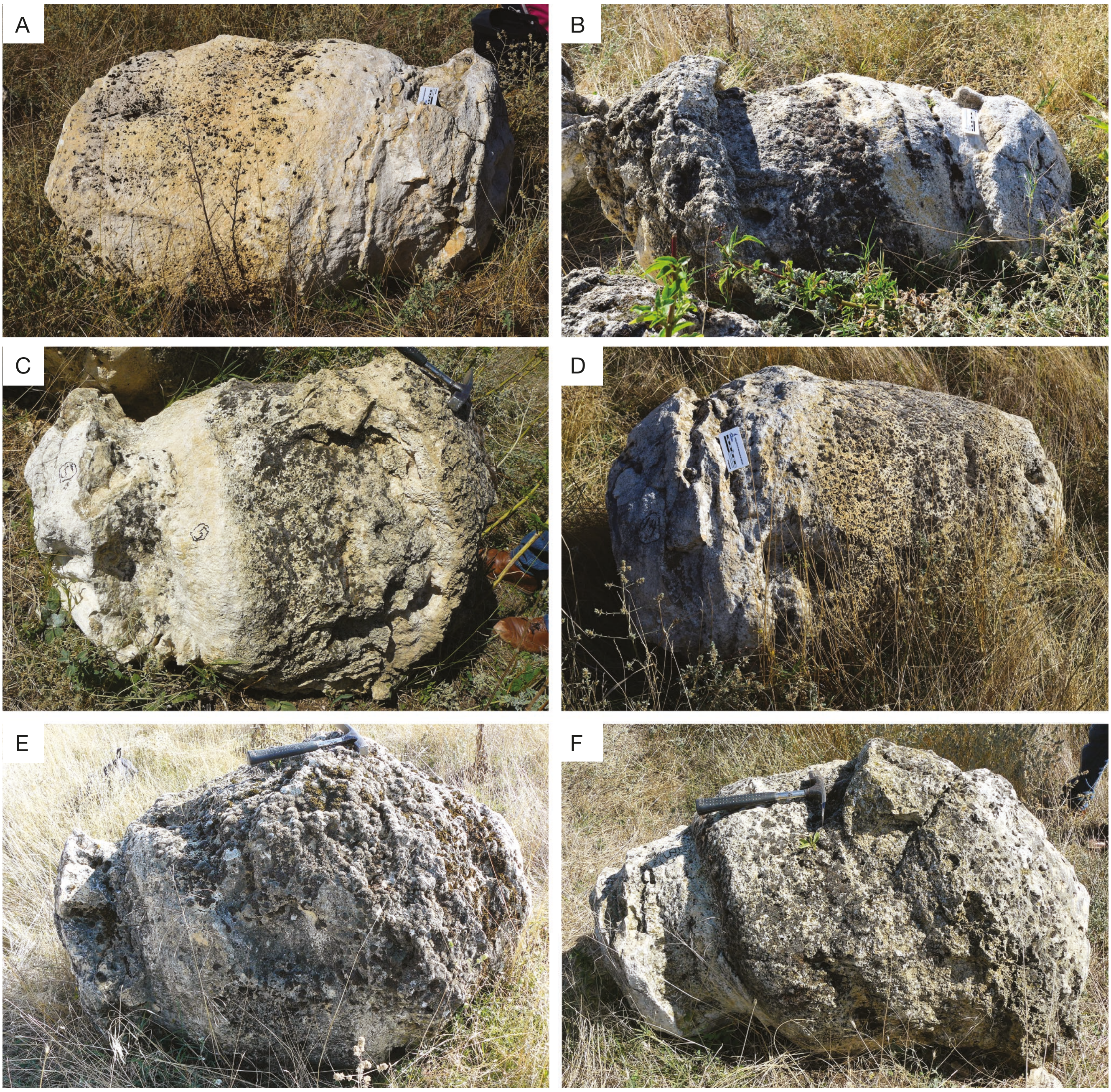


FIG. 5. — Horizontally arranged cylinders. Scale bars: A-B, D, 10 cm; C, F-G: the hammer gives the scale.

## RESULTS

### FIELD OBSERVATIONS

Currently we can observe calcareous cylinders in two zones (Fig. 2) separated by a thalweg. The zone 1 (Fig. 3) displays numerous displaced cylinders, mainly grouped and arranged horizontally, more rarely artificially replaced in a vertical position. Other cylinders are still preserved *in situ* in their natural and vertical position. The zone 2 (Fig. 4) shows a very irregular surface topography and displays only *in situ* cylinders, sometimes barely flush with the surface. In the zone 2, the cylinders rest directly upon subhorizontal layers of oolitic and *Mactra* lumachellic sediments (Fig. 4F, G).

In both zones, the central tubes of *in situ* cylinders are quite obvious, partially filled with soil or occupied by various plants.

All of the calcareous cylinders exhibit substantially the same features that can be well observed on the horizontally arranged specimens (Fig. 5). The barrel shape is the most common. Depending on the bulge of the middle part of the cylinders, more or less flared shapes are possible. The *in situ* remained specimens (Fig. 6) never display the basal part of the entire original structures. Their upper

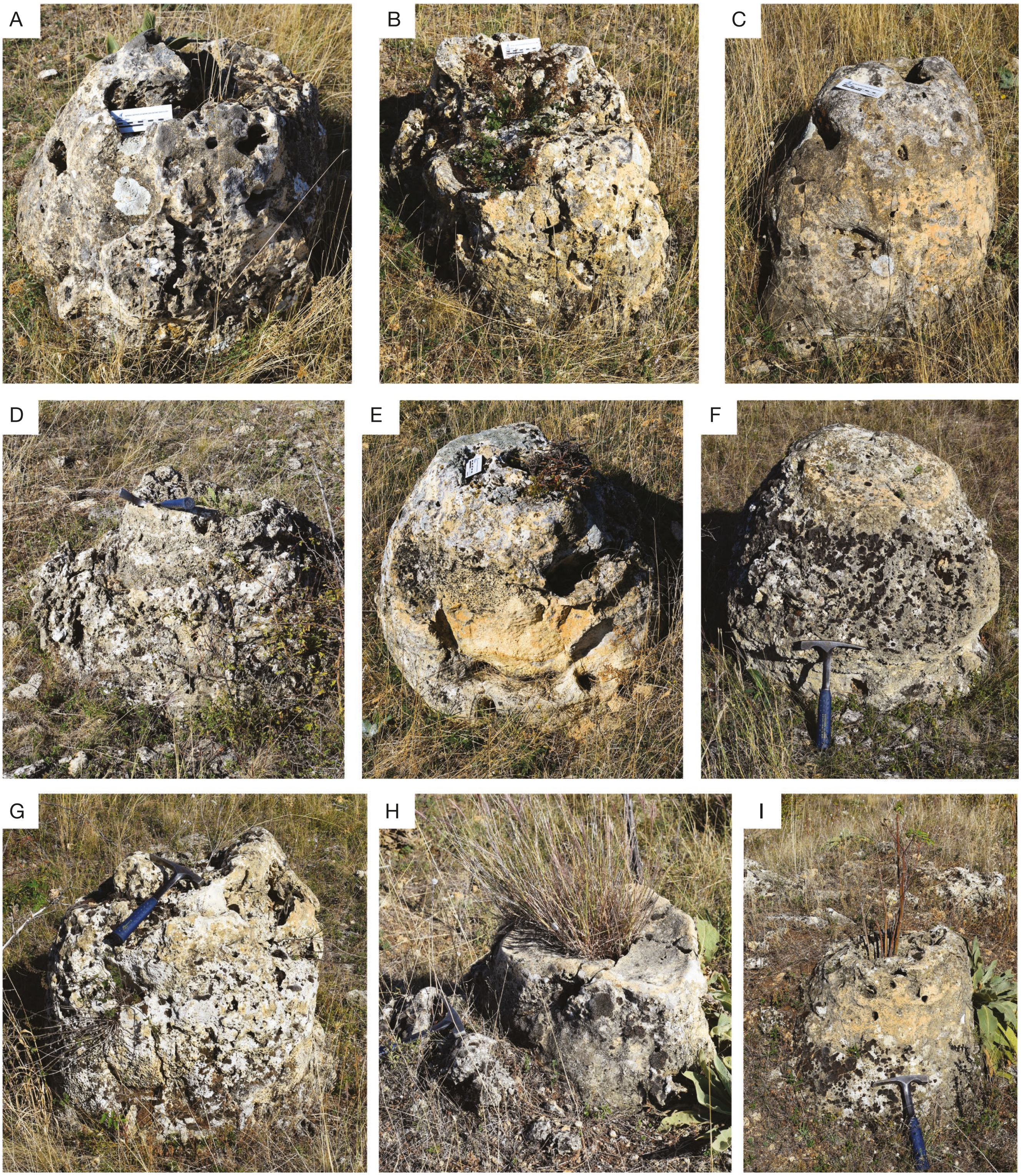


FIG. 6. — **A**-**I**, Vertically arranged cylinders in natural position; **F**, preserved dome shaped in form of “hat”; note the position of the central cavity; Scale bars: A-C, E: 10 cm; D, F-I: the hammer gives the scale.

part has often been stripped revealing the central cavity (Fig. 6). However, the top of the cylinders can be sometimes closed by a remained “hat” (Fig. 6F). The central cavity (Fig. 7) lacks a well-marked recognizable imprint on their internal wall. It is often filled by soil which has allowed the growth of different plants, like natural flowerpots (Fig. 6H). In some cases, the cavity is partially blocked by late concreted deposits.

Measurements made on the cylinders show some disparities depending on the shape (Table 1). The total length

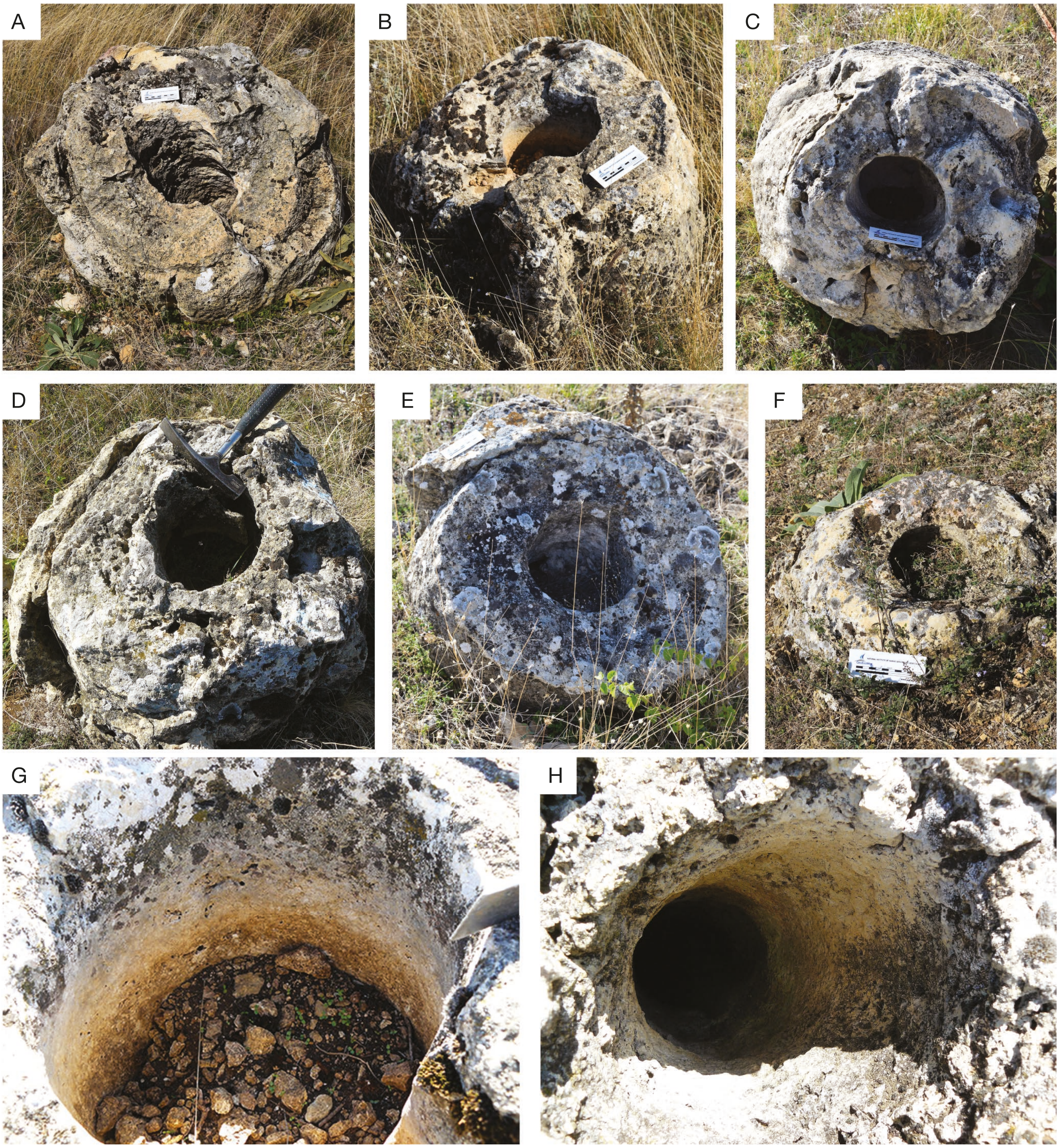


Fig. 7. — **A**-**F**, Different views of the cylinders showing the central cavity with usually smooth edges; **G**, **H**, detailed views showing the smooth internal structures. Scale bars: A-C, F, G, 10 cm; D, E, the hammer gives the scale.

ranges from 80 cm to 135 cm with an average value of 109 cm. Due to the swollen shape of the cylinders, the diameter varies from the base to the top. The diameter of the most swollen part ranges from 63 cm to 123 cm with an average value of 77 cm. The diameter of the central cavity is not always measurable. It varies from 8 to 20 cm and is not necessarily proportional to the length.

### Cylinder features

The artificially displaced cylinders in a horizontal position allow to observe the substrate on which the structures were built and their various component parts (Fig. 8). Thus, six component parts are distinguished:

– GR1: limestone layer forming the base and containing numerous internal molds of the bivalve genus *Mactra* Linnaeus, 1767;

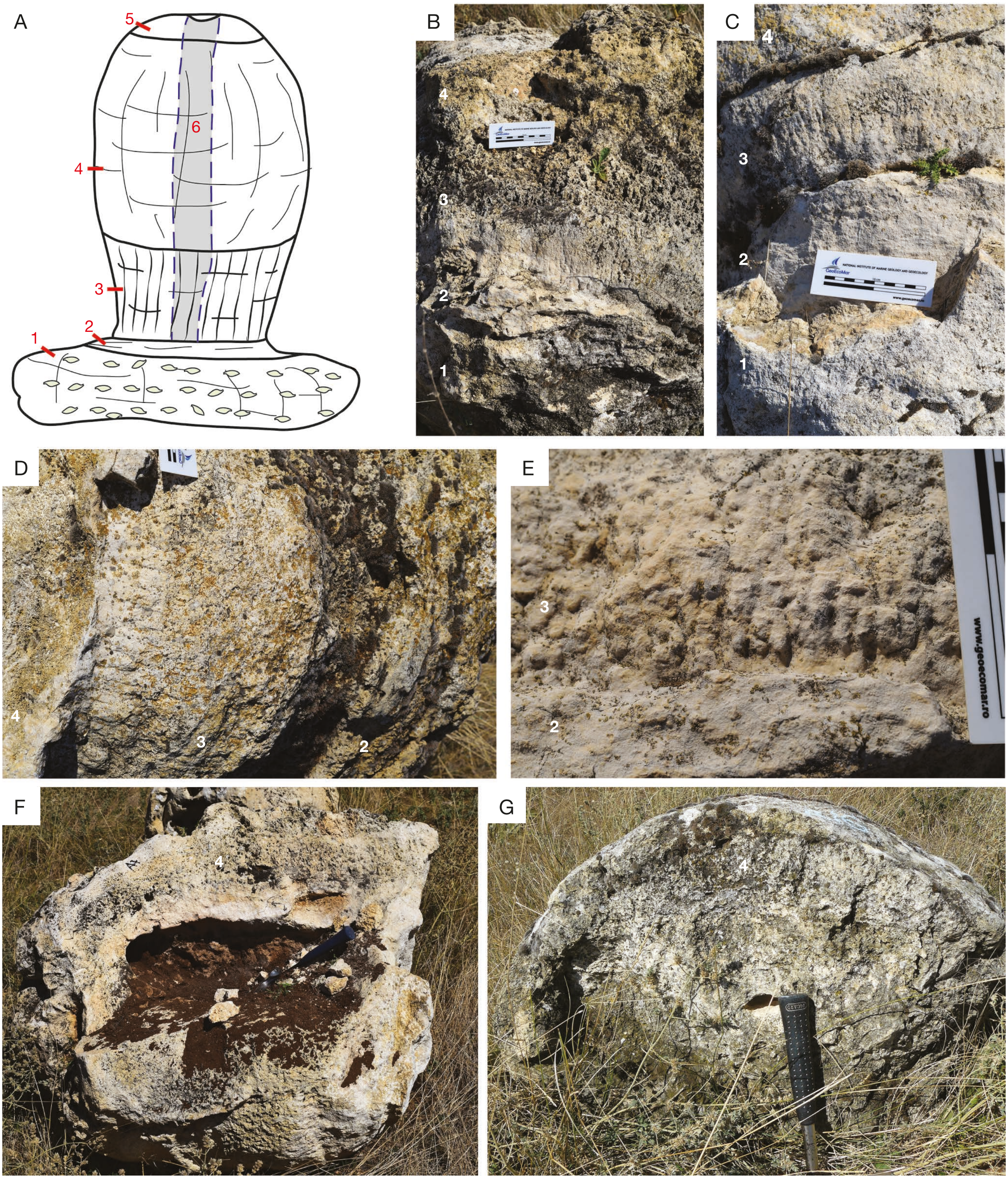


Fig. 8. — **A**, Synthetic diagram of the constitution of the cylinders: **1**, GR1, base with the *Mactra* limestone; **2**, GR2, very compact micritic thin layer; **3**, GR3, grooved limestone layer; **4**, GR4, main mass made up of concentric layers; **5**, GR5, dome-shaped top; **6**, GR6, central cavity; **B**, **C**, details of the cylinders showing the elements 1 to 4; **D**, detail of the elements 2 to 4; **E**, detail of the element 3 showing the grooved external appearance; **F**, longitudinal section of a cylinder showing the concentric layers (**4**) around the central cavity (**6**); **G**, cross section of a cylinder showing the filled central cavity and the different concentric layers (4). Scale bars: B-E, 10 cm; F, G, the hammer gives the scale.

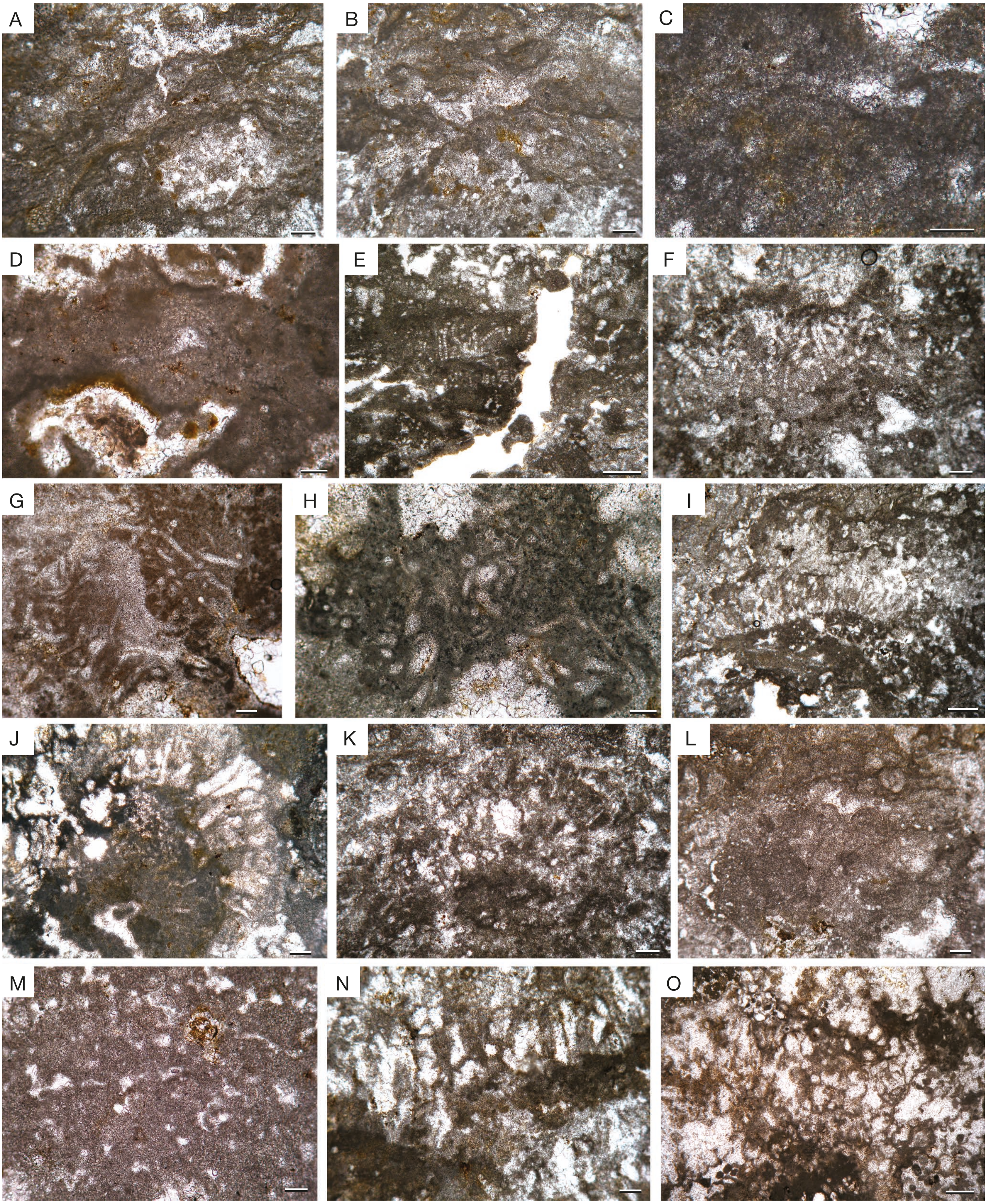


Fig. 9. — Main components of crusts: **A**, **B**, type 1, thin crust attributable to corallines; **C**, **D**, type 2, micritic masses attributable to corallines showing a preserved cellular structure; **E**, **F**, type 3, cell alignments within a micritic crust with an indistinctly fine structure, possibly attributable to Corallinaceae; **G**, **H**, type 4, networks of filaments with micritic outlines within micritic masses, recalling a cyanobacterial structure of the *Girvanella* type; **I**, **J**, type 5, elongated cell structures, sometimes branched; **K**, type 6, rounded micritic masses with fine fan-shaped filaments recalling small cyanobacterial constructions; **L**, **M**, type 7, lumpy micritic clumps of probable microbial origin; **N**, **O**, type 8, cellular structures of variable size exhibiting a *Bacinella*-like character. Scale bars: A, F, J-L, 200 µm; B-D, G, H, M, N, 100 µm; E, I, O, 500 µm.

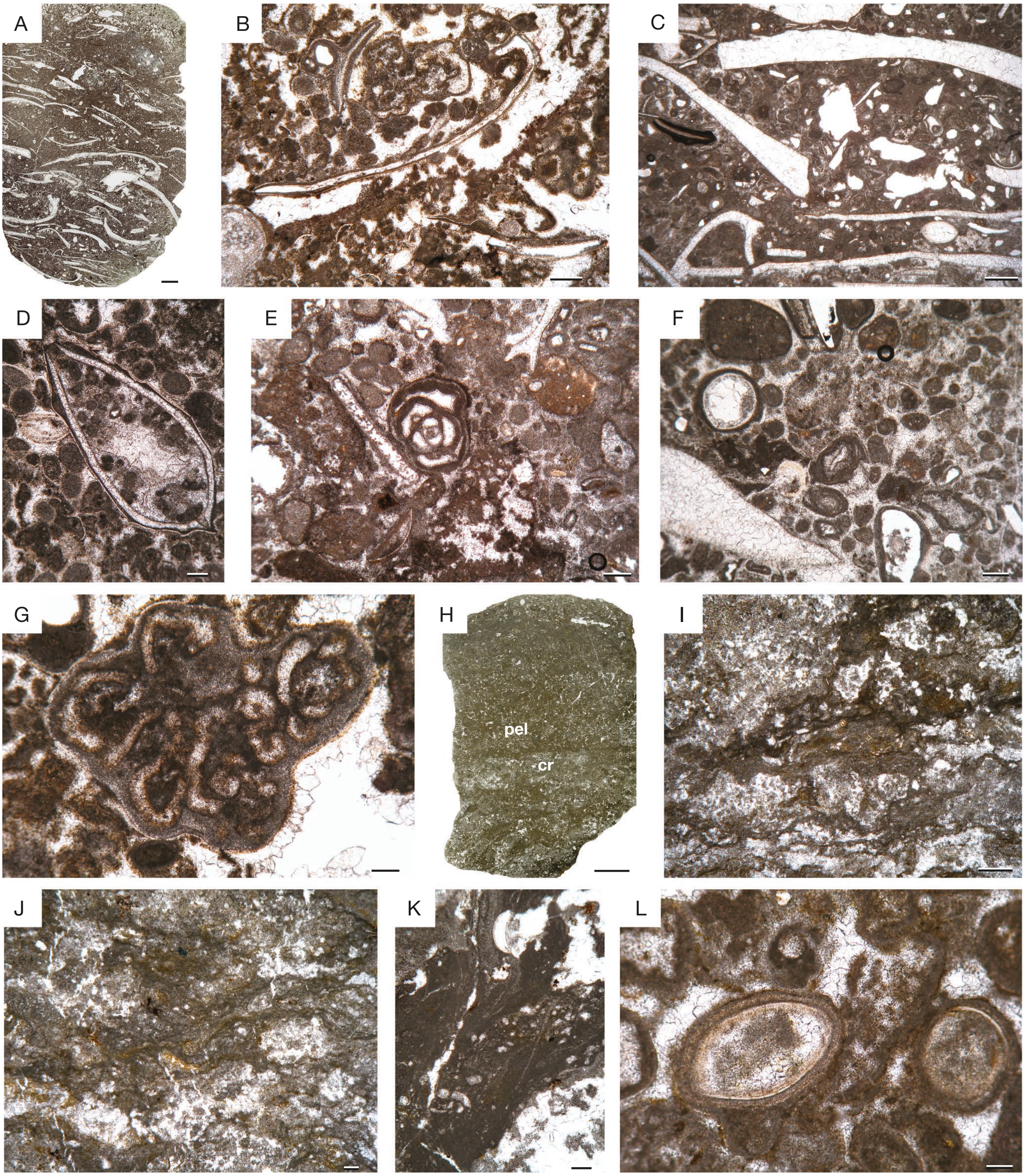


Fig. 10. — **A**-**G**, GR1 *Mactra* limestone microfacies; **A**, overview showing horizontal deposit of disarticulated *Mactra* shells; **B**-**D**, *Mactra* valves within peloidal sediment; the structure of pellets recalls faecal pellets; **E**, porcelaneous nubecularid test; **F**, sediment with peloids and oolites showing variable nuclei; **G**, undetermined honeycomb bioclasts; **H**-**L**, GR2 microfacies; **H**, general view showing the succession of micritic crusts (cr) and peloid accumulations (pel); **I**, thin crusts (type 1) attributable to Corallinaceae; **J**, thin crusts (type 1) attributable to Corallinaceae; **K**, very micritized corallinaceous crust (type 2), revealing thin lines of cells; **L**, ostracod shells with finely oolitized outlines within the peloidal sediment. Scale bars: A, E-G, J, K, 200 μm; B, C, I, 500 μm; D, L, 100 μm; H, 5 mm.

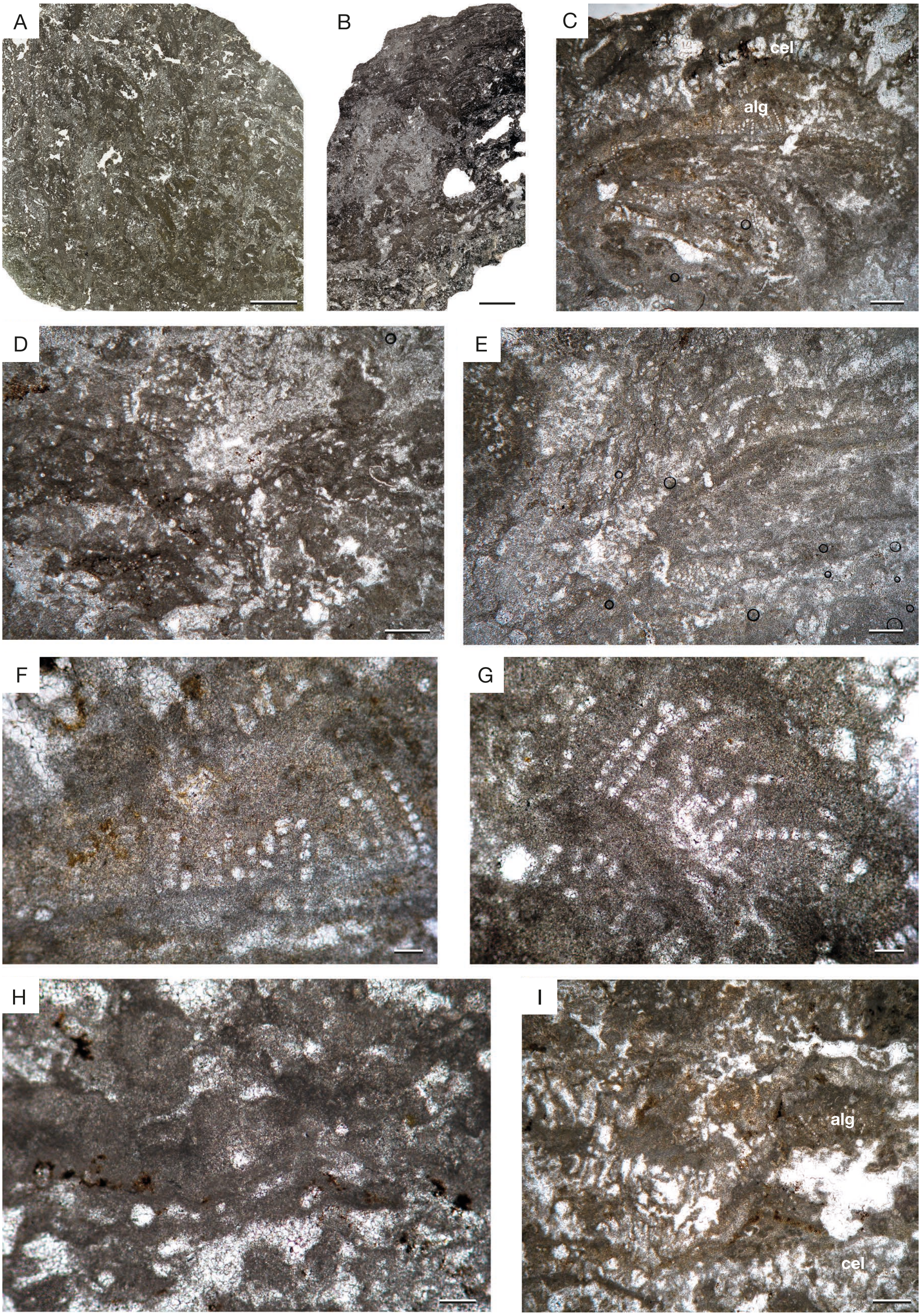


Fig. 11. — GR3 microfacies: **A**, **B**, general views showing dense micritic crusts, often forming small columns; **C**, detail of a multi-component crust: probable algae (type 3) with alignments of large cells (**alg**) and type 5 cell structures (**cel**) erected on the previous algal crust; **D**, **E**, mass formed by successive fine crusts (type 1) and rows of cells (type 3); **F**, **G**, detail of the rows of algal cells (type 3); **H**, lumpy micritic masses of microbial origin (type 7); **I**, composite crust with fine algal crusts (type 1), rows of cells (type 3, **alg**), cellular structures (type 5, **cel**). Scale bars: A, B, 5 mm; C, D, I, 500 μm; E, 400 μm; F-H, 100 μm.

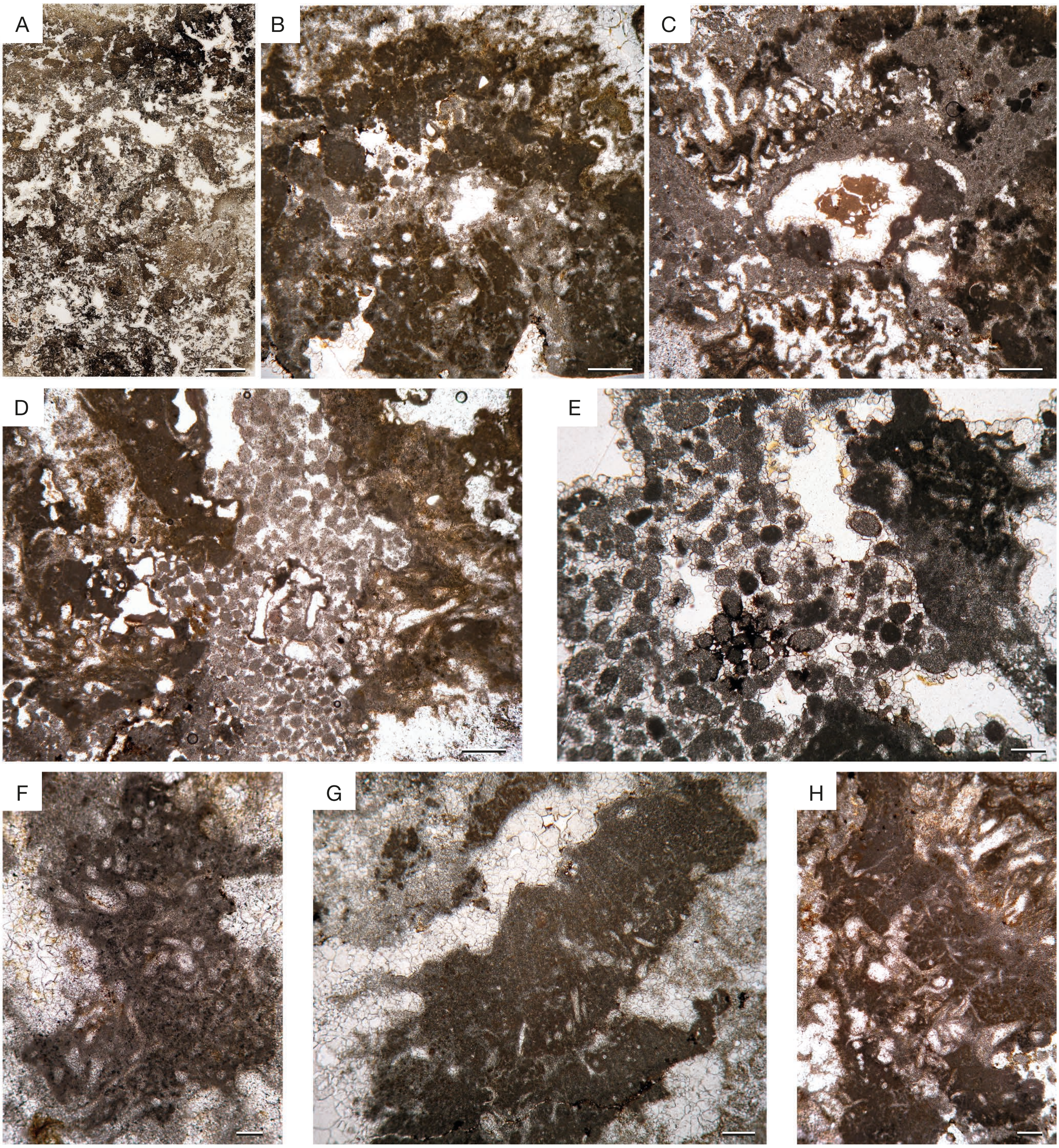


FIG. 12. — GR4 internal part microfacies; **A**, overview showing the porosity determined by the voids, partially filled by peloidal accumulations between the micritic columns; **B**, detail of peloids showing features of faecal pellets; **C**, cellular structures (type 5); **D**, **E**, spaces between columns filled by peloidal accumulations; **F**, **G**, micritic clusters containing intertwined filaments (type 4); **H**, composite crust with elongated filamentous and cellular structures. Scale bars: A, 5 mm; B-D, 500 µm; E, H, 200 µm; F, G, 100 µm.

– GR2: layer of a few centimeters thick consisting of a dense finely bedded limestone;

– GR3: very dense, hard, micritic layer marked by vertical grooves;

– GR4: calcareous mass with three major successive distinct concentric layers (GR4a, GR4b and GR4c from inside to outside), partly warty and porous;

– GR5: limestone "hat" covering the central cavity;

– GR6: central tubular cavity.

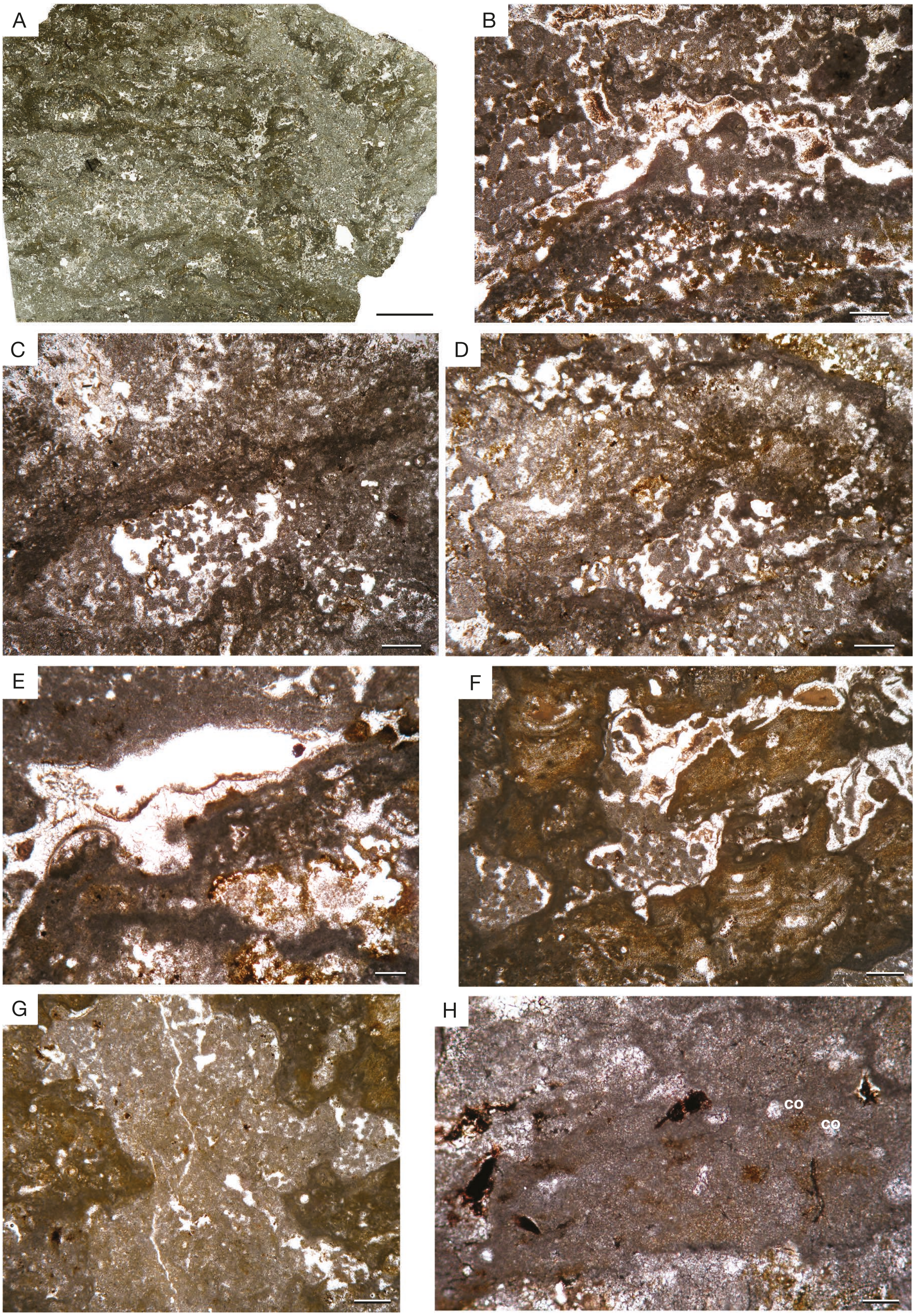


Fig. 13. — GR4 middle part microfacies; **A**, general view showing crusts forming more or less wide columns, the spaces between the columns being filled by peloidal accumulations; **B**, details of micritic and peloid crusts; **C**, thin crusts (type 1) and peloids; **D**, composite crusts with algae and vacuolar structures (type 8); **E**, detail of cell-lined crusts (type 3) and presence of ostracod shells; **F**, finely rolled columns (microstromatolites?) with filling of voids by peloids; **G**, filling of a void between two micritic crusts by peloidal accumulations; **H**, crust (type 2) of Corallinaceae whose cell structure is degraded by an intense micritization, but with distinguishable conceptacles (**co**). Scale bars: A, 5 mm ; B-D, F, G, 500 µm; E, 200 µm; H, 100 µm.

Main organic crust components

From the different parts GR2 to GR5 recognized above, crusts of various natures are observed. The poor preservation, particularly resulting in micritization to microsparitization, generally do not usually allow a precise identification of the nature of these crusts.

– type 1: the most frequent crusts consist of thin micritic inframillimetric overlays; their arrangement and appearance, as well as the presence of pores similar to reproductive cells, suggest a corallinaceous algal nature (Fig. 9A, B) without a more precise taxonomic identification;

– type 2: crusts or areas thicker than those of type 1 display more or less clearly preserved structures like corallinaceous thalli; these are the rows of rectangular cells and the conceptacles of semicircular shape in section with a vaulted arrangement of the cells (Fig. 9C, D);

– type 3: other areas show alignments of larger cell structures with micritic walls and interior filled with calcitic cement on a very micritized background (Fig. 9E, F); these features suggest reproductive organs within thalli of corallinaceous algae but other origins are possible;

– type 4: micritic masses constituted from an entanglement of filaments (Fig. 9G, H) represents another organic structures; these entwined, sinuous or partly rectilinear tubular filaments have a variable diameter, from 20 to 60 µm with a micritic wall thickness of the order of 10 to 20 µm; their identification is quite uncertain; the appearance could evoke stems of the green algae *Cladophorites* as has already been reported in organic constructions from the Sarmatian of Hungary (Saint Martin *et al.* 2009) but the size and length of *Cladophorites* are by far larger (Riding 1979) and their filaments are commonly branching and partings can be eventually seen; finally, observed filaments in our material fit more like with cyanobacterial filamentous structures of the *Girvanella* type;

– type 5: elongated cellular structures marked by a micritic outline and sometimes coarse ramifications are also observable, but their nature is difficult to determine (Fig. 9I, J).

– type 6: other rounded masses are characterized by the presence of filaments with a diameter of around 40 µm erected in a fan (Fig. 9K); the cyanobacterial nature of these crusts is probable.

– type 7: lumpy, cloudy, sometimes peloidal micritic masses indicate a probable microbial fabric (microbialite) (Fig. 9L, M).

– type 8: numerous vacuolar structures with micritic outlines and size of the order of several hundred microns also participate in crusts (Fig. 9N-O); these could be *Bacinella*-like microbial structures well known in the Mesozoic (Granier, 2021), but plant-cell calcification remains cannot be ruled out.

Microfacies

*GR1 (Fig. 10A-G)*

It is a packstone to grainstone lumachellic bioclastic limestone (Fig. 10A). The remains of bivalves belong only of the genus *Mactra* (Fig. 10B-D). The shells of *Mactra*, usually laid out flat, mostly disarticulated, are completely dissolved and then the moldic porosity was partially filled with microsparite. The other faunal constituents are not very diversified, mainly represented by ostracods with fine and smooth shells (Fig. 10D, L). Foraminifera are only represented by a few specimens of solitary nubecularids (Fig. 10E), probably similar to *Nubecularia novorossica* (Karrer & Sinzow, 1877) cited in the Bessarabian from Bulgaria (Koleva-Rekalova & Darakchieva 2019). The grains are mainly peloids and ooids (Fig. 10F). Bivalve and ostracod shell fragments can be surrounded by a thin oolitic crust and even be taken up in composite oolitic aggregates. Some elements, quite numerous, which appear as aggregates containing several rounded tubular-looking bodies are not formally identified (Fig. 10G).

The siliciclastic part is represented by very rare grains of oolitized quartz. Calcitic cement ensures a good cohesion.

*GR2 (Fig. 10H-L)*

The very dense GR2 facies is a framestone (Fig. 10H) made up of algal-crust sequences of types 1 (Fig. 10I, J) and 2 (Fig. 10K) separated by one centimeter-thick oolitic layers. Oolitic grains have various nuclei, sometimes consisting of ostracod shells (Fig. 10L).

*GR3 (Fig. 11)*

The GR3 facies, mainly micritic, appears as a framestone with a very dense network formed by columnar structures delimiting spaces filled by peloids (Fig. 11A, B). The components are mainly crusts of types 1 (Fig. 11D, E, I), 3 (Fig. 11C, E-G, I), 7 (Fig. 11H), 5 (Fig. 11C, I), and 7 (Fig. 11H).

*GR4 (Figs 12-14)*

Most of Gramada cylinders are made up of three well-defined concentric limestone layers.

The densest internal part GR4a (Fig. 12) is of the framestone-grainstone type (Fig. 12A-C). The frame is characterized by millimeter-thick columns and / or intermittent micritic crusts delimiting voids filled by a sediment consisting mainly of peloids and more rarely ooids (Fig. 12D, E). The crusts are of various natures, sometimes overlapping. Much of them consists of clusters showing type 4 filaments (Fig. 12F, G). Elongated type 5 cell structures (Fig. 12H) are also involved, but to a lesser extent. The peloids have a rounded appearance and have a fine-grained microstructure with many micropores, characteristics evoking faecal pellets, the pores corresponding to the passage of the excretory sieve of small arthropods.

The middle part GR4b is quite similar to the previous one with also small columns and crusts (Fig. 13A) where the components of types 1 (Fig. 13C), 2 (Fig. 13H), 3 (Fig. 13E), and 8 (Fig. 13D) are represented. We further observe in some samples a mass formed of millimetric microstromatolitic columns, of probable microbial origin (Fig. 13F). The filling is also essentially peloidal in nature.

The outermost part GR4c, when well preserved, is clearly more porous. The millimeter to centimeter thick columns that make up the framework are more clearly defined (Fig. 14A-C) leaving empty spaces or partially filled with peloidal and partially oolitic sediment. The network is composed of cell masses of types 5 and 6 (Fig. 14D), and components of types 1 to 4 (Fig. 14E-G). Peloids (Fig. 14H) probably correspond

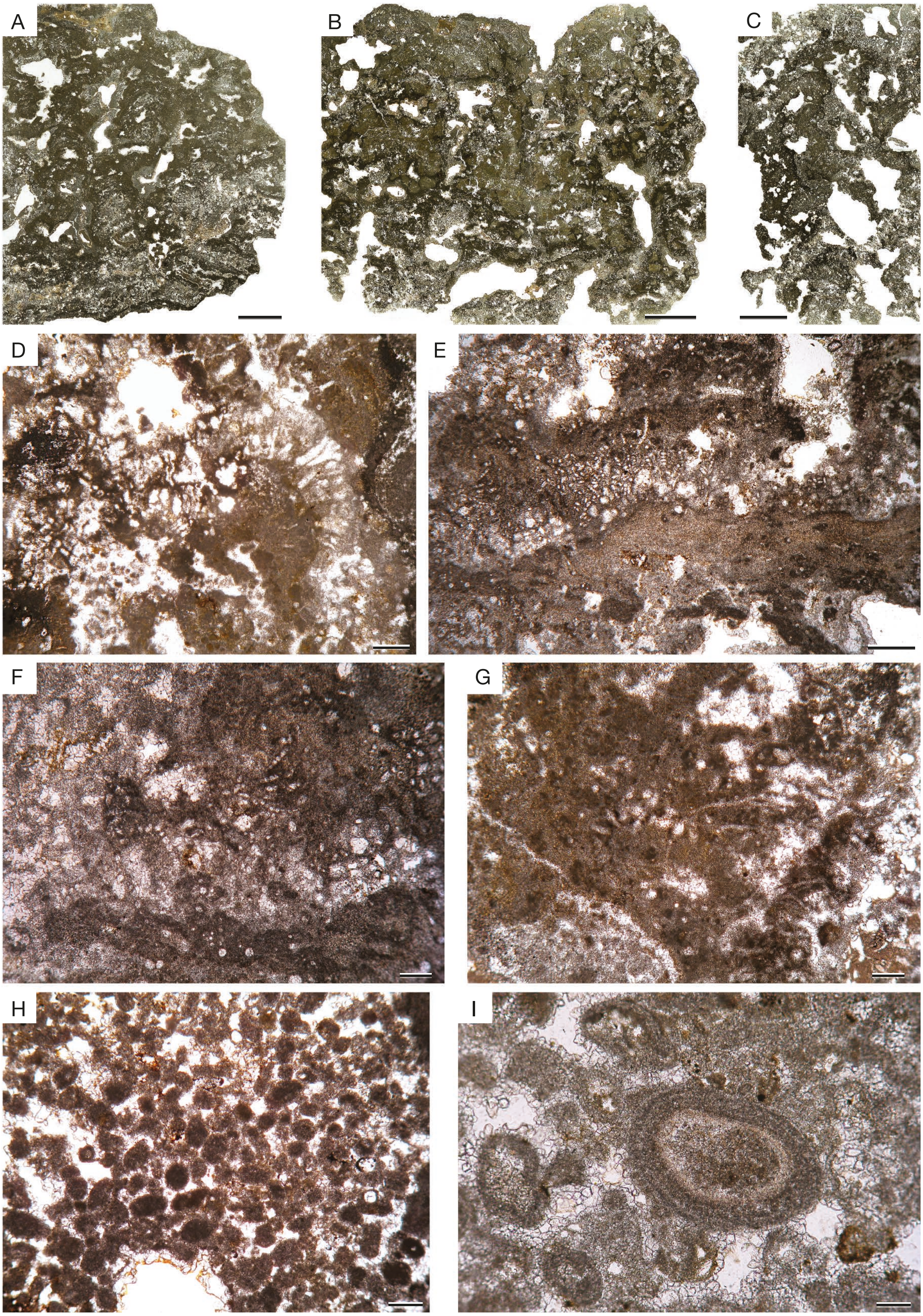


Fig. 14. — GR4 outer layer microfacies; **A**-**C**, general views showing the appearance in micritic columns making spaces partially filled by peloidal and oolitic accumulations; **D**, filamentous crusts surrounded by elongated branched cellular structures (type 5); **E**, composite corallinaceous crusts (types 2 and 3);. **F**, cellular crusts (type 3); **G**, crust with *Girvanella*-like filament; **H**, accumulations of peloids resembling faecal pellets; **I**, details of grains with an oolitic cortex. Scale bars: A-C, 5 mm; D, E, 500 µm; F-H, 200 µm; I, 100 µm.

here also to faecal pellets. The ooids are formed around various nuclei including peloids themselves (Fig. 14I). A calcitic cement partially fills the voids (Fig. 14I).

*GR5 (Fig. 15)*
The dome-shaped top of the cylinders ("hat") is due to a limestone close to the previous facies. This is a framestone with a predominantly oolitic filling (Fig. 15A, B). The thick overlying crusts involve various components of types 1,2,7 and 8 (Fig. 15C-H). Oolitic cortices coat various bioclasts and sometimes form lumps (Fig. 15I).

## DISCUSSION

### Nature of crusts and comparisons

*Originality of the crusts*
The calcareous crusts of Gramada display interesting original features. The entire micritic nature of the crusts is the most remarkable mineralogical aspect. Other similar geological objects usually result from mineralization processes specific to the formation of travertines. Only a drusic calcitic cement, filling the voids (mold cement), is observable and ensures the cohesion of the construction, especially for the most porous parts. The crusts themselves result from the aggregation of small fine micritic masses giving a discontinuous appearance in detail. No obvious stromatolite-type lamination is expressed. However, the microbial influence can be identifiable in small scattered masses in which cyanobacterial filaments are suspected and in clumps of cloudy lumpy micrite. Finally, the successive crusts, whatever their appearance, seem to result mainly from the activity of corallinaceous algae (types 1 to 3), filamentous networks (type 4) and to a lesser extent from lumpy masses (type 7) or cellular structures (type 8).

*Paleoecological meaning of the crusts*
We can undoubtedly determine the corallinaceous algal nature of several crusts (type 1, type 2 and possibly type 3) without identifying precise taxa. Indeed, the pronounced micritization of the thalli very seriously obliterated their original fine structures which appear only on a few areas of well-preserved cells. The micritization, probably of microbial origin, of corallinaceous algae is a phenomenon observed in marine carbonate environments on recent algal formations (Wolf 1965; Siblay & Murray 1972; Gunatilaka 1976; Martindale 1992; Nebelsick & Bassi 2000). In marine Miocene carbonate environments, the micritization of the finely laminated thalli leads to difficulties in identifying their algal nature itself and even more so in their taxonomic affinity (Rösler *et al.* 2015).

The occurrence of corallinaceous calcareous algae in carbonate formations from the Sarmatian of Paratethys is infrequently mentioned. In the Lower Sarmatian of the Vienna Basin (Austria), corallinaceous algae belonging to the genera *Lithophyllum* Philippi, 1837 and *Melobesia* Heydrich, 1897, were first described by Kamptner (1941). Several studies devoted to the Austrian Sarmatian then shown the implications of these algae in composite constructions: nubecularids, bryozoans, serpulids and microbialite (Friebe 1994a, b; Harzhauser & Piller 2004a, b; Harzhauser *et al.* 2006). In several regions of Romania, corallinaceous algae are also known in composite Sarmatian carbonate constructions containing microbialites, serpulids and bryozoans (Bucur *et al.* 1992, 1993; Saint Martin & Pestrea 2000). A systematic study of the calcareous algae from the Volhynian (lower Sarmatian) of Romania (Bucur *et al.* 1993) mentions three species of Corallinaceae belonging to the genera *Titanoderma* Nägeli, 1858, *Lithoporella* Foslie, 1909, and *Corallina* Linnaeus, 1758, also associated with composite constructions containing microbialites, serpulid and bryozoa. In Hungary, the occurrence of corallinaceae (*Lithoporella*, *Lithophyllum*, *Titanoderma*, etc.) in lower and upper Sarmatian deposits was demonstrated in carbonate platform facies in association with microbialite, serpulid and bryozoan constructions (Cornée *et al.* 2009; Saint Martin *et al.* 2009). Corallinaceous algae are rather considered as a minor participant of the carbonate sedimentation in the other areas of the Paratethys (Pisera 1985, 1996). The discovery of Corallinaceae in the Bessarabian crusts of Gramada is therefore a confirmation of a constancy of their occurrence during the entire Sarmatian time and joins the findings made on very similar carbonate platforms in Romania, southern Dobrogea (Saint Martin *et al.* 2013 and personal observations). Moreover, Corallinaceae are usually considered to be rather stenohaline organisms, which constitutes one of the arguments for invoking the existence of an influence of marine waters during the Sarmatian in Paratethys (Piller & Harzhauser 2002, 2005).

As mentioned above, the small masses or crusts containing filaments with more or less intermixed micritic outlines correspond to a structure to be compared to cyanobacterial *Girvanella*-like filaments. It was considered that such calcified filaments would come mainly from freshwater sediments (Colin & Vachard 1977; Bignot 1981) after the Early Cretaceous. Recent calcified filamentous cyanobacteria (e.g., *Plectonema* Thuret ex Gomont, 1892) also growing in freshwater microbialites were considered to be extant forms responsible for *Girvanella*–like structures (Riding 1977; Krumbein & Potts 1978; Laval *et al.* 2000). However, Friebe (1994) reported the presence of calcified *Girvanella*-like cyanobacterium filaments in a carbonate biostrome from the Austrian Sarmatian, considered to be brackish. According to Saint Martin (2010), marine microbialites of Messinian age still contain such filaments. Regardless, this type of filament is associated with microbial buildups, as is the case with cylinders of Gramada.

### Associated biota

During the Sarmatian, paralic environments were set up whose biodiversity depended on brief marine communications (Piller and Harzhauser, 2005; Piller *et al.*, 2007). New kinds of reefs due to microbial activity in association with bryozoans and serpulids produced large carbonate masses while the sea bottoms were mainly populated by molluscs showing an increasingly pronounced endemic character. Biodiversity has been considerably reduced with the disappearance of many stenohaline faunal groups such as corals, echinoderms, brachiopods and very many families of both bivalves and gastropods.

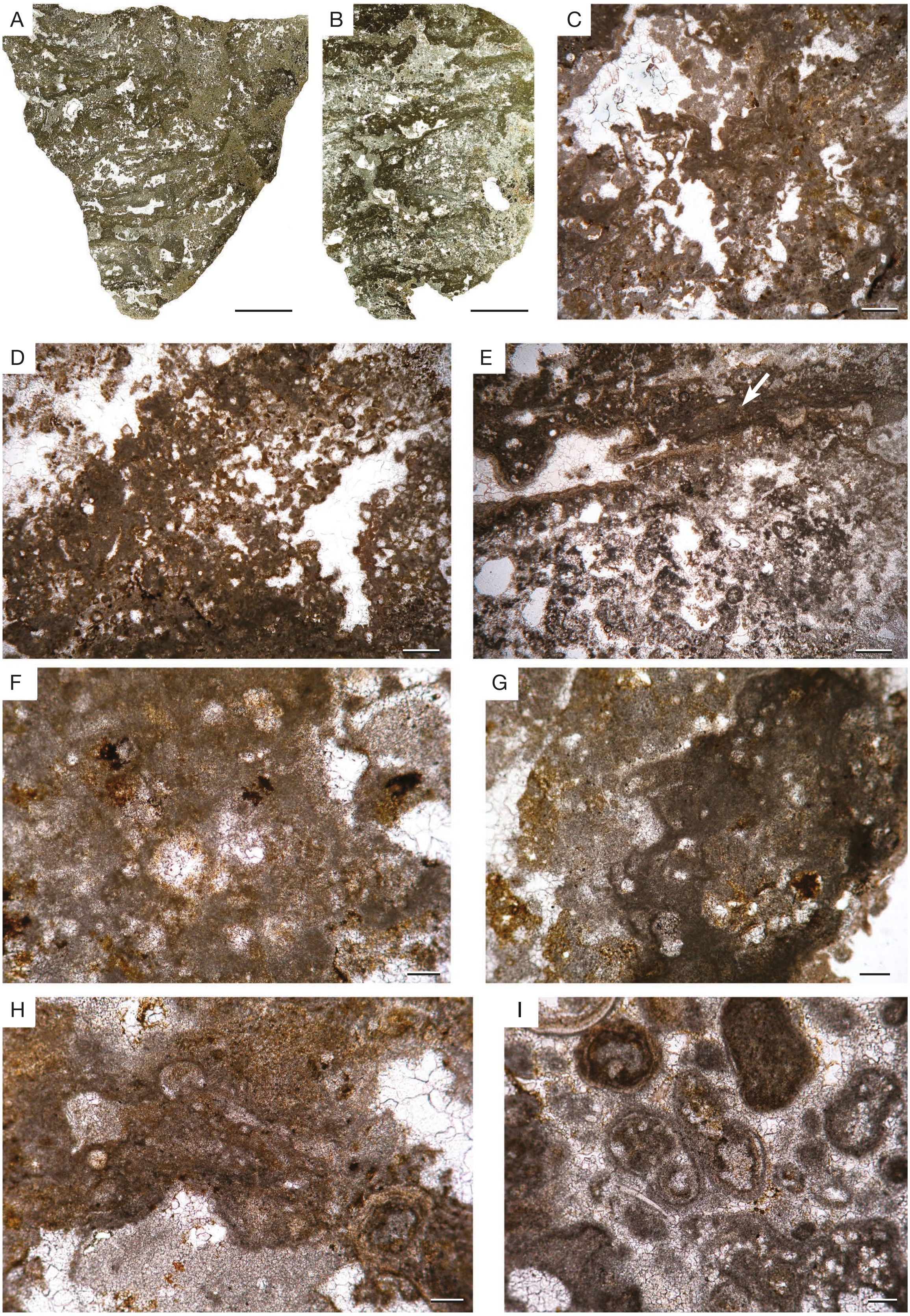


Fig. 15. — GR5 dome-shaped top microfacies; **A**, **B**, general views showing dense micritic crusts; **C**, detail of micritic columns; **D**, partially peloidal micritic crust with poorly expressed filamentous structures; **E**, composite micritic crust with very degraded corallinaceous crusts and fine filamentous structures (arrow); **F**, **G**, corallinaceous crusts (type 2) showing fairly well-preserved cell structures; **H**, probable corallinaceous crust; **I**, accumulations of peloids often oolitized and bioclasts with undetermined honeycomb structures (see Fig. 10G). Scale bars: A, B, 5 mm; C, D, 500 µm; E, 200 µm; F-I, 100 µm.

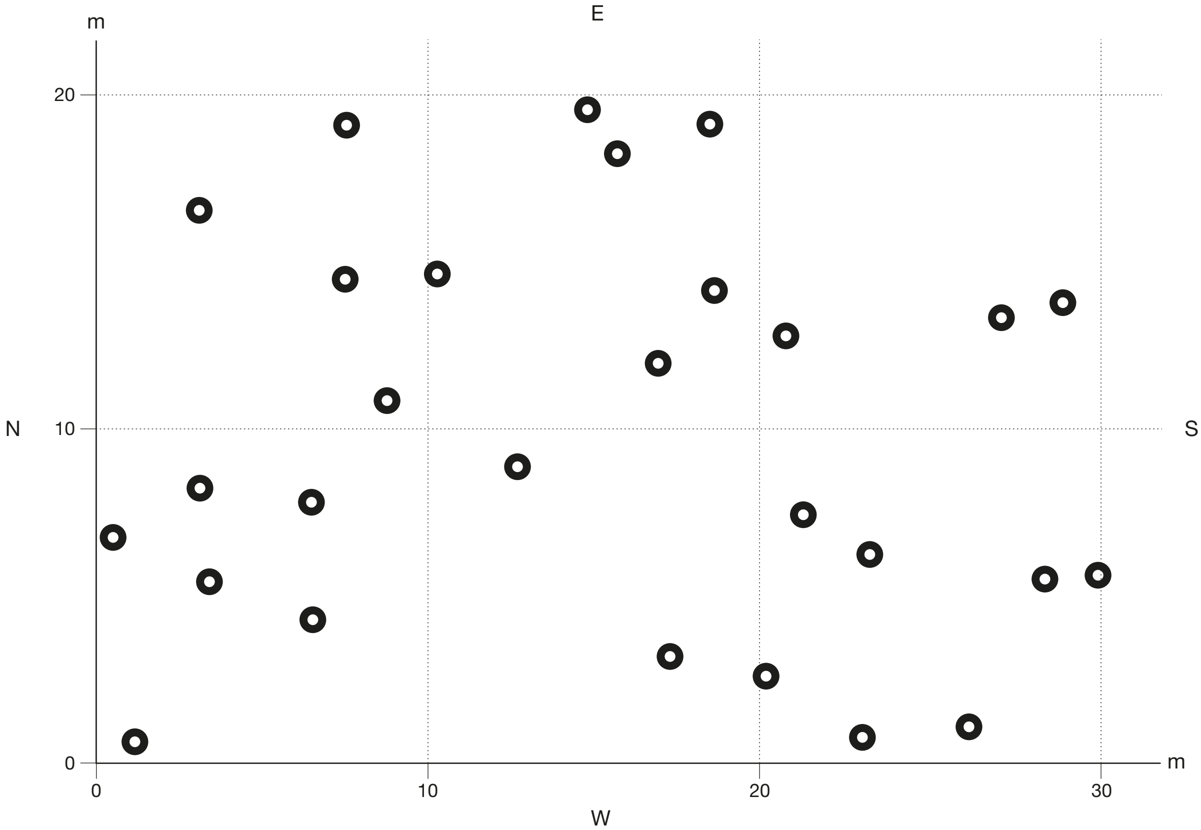


Fig. 16. — Spatial distribution of cylinders remaining *in situ* from zone 1, giving an idea of their density on the field.

Then, carbonate platforms characterized by abundant oolitic material and the abundant production of euryhaline mollusc shells developed in the shallow basins. The Gramada cylinders were set up in this particular context of shallow paralic basins, which could be subject to temporary emersion.

Apart from the main components of the crusts described above, the associated biota of Gramada cylinders, is extremely poor. The most common identifiable organisms are ostracods represented by thin shells, sometimes taken up by thin oolitic laminations. No mollusc shells were observed within the encrusting sequences. The lack of foraminifers usually abundant in the Sarmatian carbonate sediments, such as the benthic foraminifera *Ammonia* Brünnich, 1771, or *Elphidium* Montfort, 1808, should be noted. Likewise, the virtual lack of nubecularids is remarkable, although they can constitute a part of certain small constructions in the underlying layers of Gramada. Finally, the lack of bryozoans usually abundant in the Sarmatian limestones of Paratethys is also to be noted. All these indices suggest that during the formation of the crusts, the waters were unfavorable to the biodiversity. This observation contrasts with a larger biodiversity usually known in the Sarmatian carbonate environments from the Paratethys. At Gramada, the lack of typical marine or brackish biota of the Sarmatian, just above the *Mactra* beds, could rather indicate the establishment of a freshwater regime. But on the other hand, no element of freshwater lacustrine biota, such charophytes or molluscs (as planorbids or limneids), is clearly detectable. Only the smooth-shelled forms of ostracods, unfortunately indeterminable, could be a non-decisive indication of a freshwater environment. Finally, the participation of corallinaceous algae seems to contradict the hypothesis of a freshwater formation. This is where the difficulty lies in determining the exact nature of certain Sarmatian aquatic environments.

### Formation modalities of cylinders

Observations performed on a very large number of structures show the uniformity of the encrusting sequence. Only the dimensions and the general shape can vary but within a fairly small margin. The problem is therefore to reconstruct the sequence and the nature of the different components. The base of Gramada cylinders consists of oolitic sands (EL1) fixed by fine algal crusts (EL2) and was originally intended to constitute a still fairly soft substrate. According to Sinyovski (2009), the hypothesis that "chuturites" are carbonate formations embedded in tree trunks seems the most plausible, because the walls are perfectly smooth and concentric in appearance. The height of the cylinders is limited to 2 m at the most and could correspond to the water level at the end of the constructions. The fact that the top of some cylinders is completely covered by "hat" seems to be related to the height of the corresponding plant remains.

No remains or imprints can establish the nature of any plants. In addition, the entire length of the central cavities was only observed in very few cylinders. The main problem is to know whether the crust was developing around residual trunks from a remnant of dead forest then invaded by water rich in CaCO3 or around plants growing more or less concomitantly. The succession of the different constitutive elements (GR2 to GR5) of the cylinders does not show any remarkable discontinuities between the *Mactra* layer and the concentric crusts. Considering the outcrop conditions, it is not possible to distinguish roots that would penetrate into the base sediment. For Sinyovski (2009), plants could be of the horsetail or bamboo type. Cenozoic horsetails can be ruled out unambiguously. The encrustation around bamboo stems, terrestrial plants, would imply the hypothesis of the remains of pre-existing forest of bamboos. Nevertheless, the presence of reeds in a lake environment is possible. Either way, we can notice that the grooved and articulated structure of these plants is not preserved by crusts. The hypothesis of a mangrove-type plant formation could represent an alternative allowing several of the necessary conditions to be met, such as the number, density (Fig. 16) and the limited height of the cylinders. Thus, in mangrove environments, where there are shallow waters, the new shoots have the appearance of vertical sticks of metric size, of variable diameter, and with a pointed top before the foliage development. Signs of the presence of mangroves are reported during the Badenian (= Langhian), just prior to the Sarmatian, in the Paratethys area (Kókay 2013) probably in relation to the development of coral reefs. Although no mention is made of the Sarmatian period, the presence of pollens of *Avicennia* Linnaeus, 1763 were reported from the upper Miocene sediments near Balchik in the northeast Bulgaria (Ivanov *et al.* 2015) and from the Pliocene in the Dacic basin (Popescu 2008). Therefore, it seems that very small and localized mangrove environments persisted until the Pliocene in the Paratethys area. According to Ivanov *et al.* (2002), the climate in the region covering northwestern Bulgaria was humid, subtropical to warm temperate still for much of the Bessarabian time, therefore during the cylinder formation.

## CONCLUSION

The calcareous cylinders of Gramada constitute an exceptional case of encrusting sequence in a paralic environment with a strong participation of calcareous algae in the construction. Their spectacular appearance is due to the uniformity of morphology and composition of all the cylinders and their high density, rightly evoking a "petrified forest". This testifies to a precise, arguably short moment in the sedimentary and environmental history of the Sarmatian. This study brought the maximum number observations on the field and in the laboratory (microfacies analyses), but the entire formation processes need to be clarified. A further complete geochemical study would thus be necessary to try to solve the problem of short-term variations in the environment, in order to establish a formation scenario which could then represent a particular model of carbonate construction.

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