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SEDIMENTOLOGY OF THE "ORE-BEARING DOLOMITE" OF THE KRAKÓW-SILESIA REGION (MIDDLE TRIASSIC, SOUTHERN POLAND)

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Abstract: The depositional history and facies heterogeneity of the epigenetically dolomitized Middle Triassic carbonates of southern Poland are poorly recognized, and existing concepts of fluid circulation entirely overlook the primary lithology as a factor controlling fluid flow. This study reconstructs the consecutive phases of Kraków-Silesia Sub-basin history in the Anisian and highlights their influence on the development of the so-called "ore-bearing dolomite". Extensive fieldwork and microfacies analyses were carried out in order to decipher the original depositional fabric of the ore-bearing dolomites. As a rule, epigenetic dolomitization affected a horizon of porous strata, 35 m thick and resting directly on impermeable, wavy-nodular clay-rich calcilutites of the Gogolin Formation, which represent the interval of deepest and fully marine (offshore) sedimentation. The sedimentary succession of the porous strata is bipartite. The lower part (Olkusz Beds) is composed of *Balanoglossites* and *Thalassinoides* micritic firmgrounds and peloidal packstones-grainstones, representing shoreface-foreshore facies assemblages, whereas the upper part (Diplopora Beds) consists of dolocretes, rhizolites, cryptalgal laminites, peloidal packstones-grainstones and bioturbated fine-grained dolostones, formed in a system of tidal flats and lagoons. These two parts are separated by a subaerial disconformity, which marks a sequence boundary. During emersion, the underlying deposits were subjected to meteoric diagenesis, which led to the development of moldic porosity. This combination of depositional history and diagenetic alteration determined the routes of initial migration of dolomitizing solutions on the one hand, and the location of cavern formation on the other. Owing to progressive dissolution, small caverns were changed into large karstic forms, in which the ore minerals precipitated ultimately. These findings emphasize the importance of sedimentological analysis to the understanding of the evolution of the Kraków-Silesia ore province.

Key words: ore-bearing dolomite, epigenetic dolomitization, lead-zinc mineralization, facies pattern, peritidal and subtidal facies, Middle Triassic, Muschelkalk, Upper Silesia, Poland.

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INTRODUCTION

The large lead-zinc deposits of the Kraków-Silesian ore district of southern Poland (Fig. 1) occur as kilometre-size tabular bodies, mainly within epigenetically dolomitized shallow-marine carbonates of the Lower Muschelkalk, mostly Anisian in age. Although the main phases of ore-mineral precipitation started long after dolomitization, the processes were genetically related to each other (e.g., Sass-Gustkiewicz and Dżułyński, 1998). Extensive investigations of the ores and ore-bearing dolomite, initiated 60 years ago, were based on thousands of drill cores and kilometres of mine galleries. These studies yielded 200 publications, mostly about ore-body geometry (e.g., Górecka, 1970; Szuwarzyński, 1983, 1996), mineral paragenesis and textures (e.g., Smolarska, 1968; Gruszczyk and Strzelska-Smakowska, 1978; Harańczyk, 1983; Górecka, 1996; Leach *et al.*, 1996a), ore geochemistry (e.g., Harańczyk, 1965; Zartman *et al.*, 1979; Kozłowski *et al.*, 1980; Leach *et al.*, 1996b; Viets *et al.*, 1996), horizontal and vertical range of dolomitization (Alexandrowicz and Alexandrowicz, 1960; Alexandrowicz, 1966, 1971, 1972), origin and migration of mineralizing and dolomitizing fluids (e.g., Pałys, 1967; Kozłowski *et al.*, 1980; Wodzicki, 1987; Górecka *et al.*, 1996; Sass-Gustkiewicz and Dżułyński, 1998). Only a few papers deal with the reconstruction of the sedimentary environment and facies pattern of this part of the Germanic (European) Basin in Middle Triassic time (Pawłowska and Szuwa-

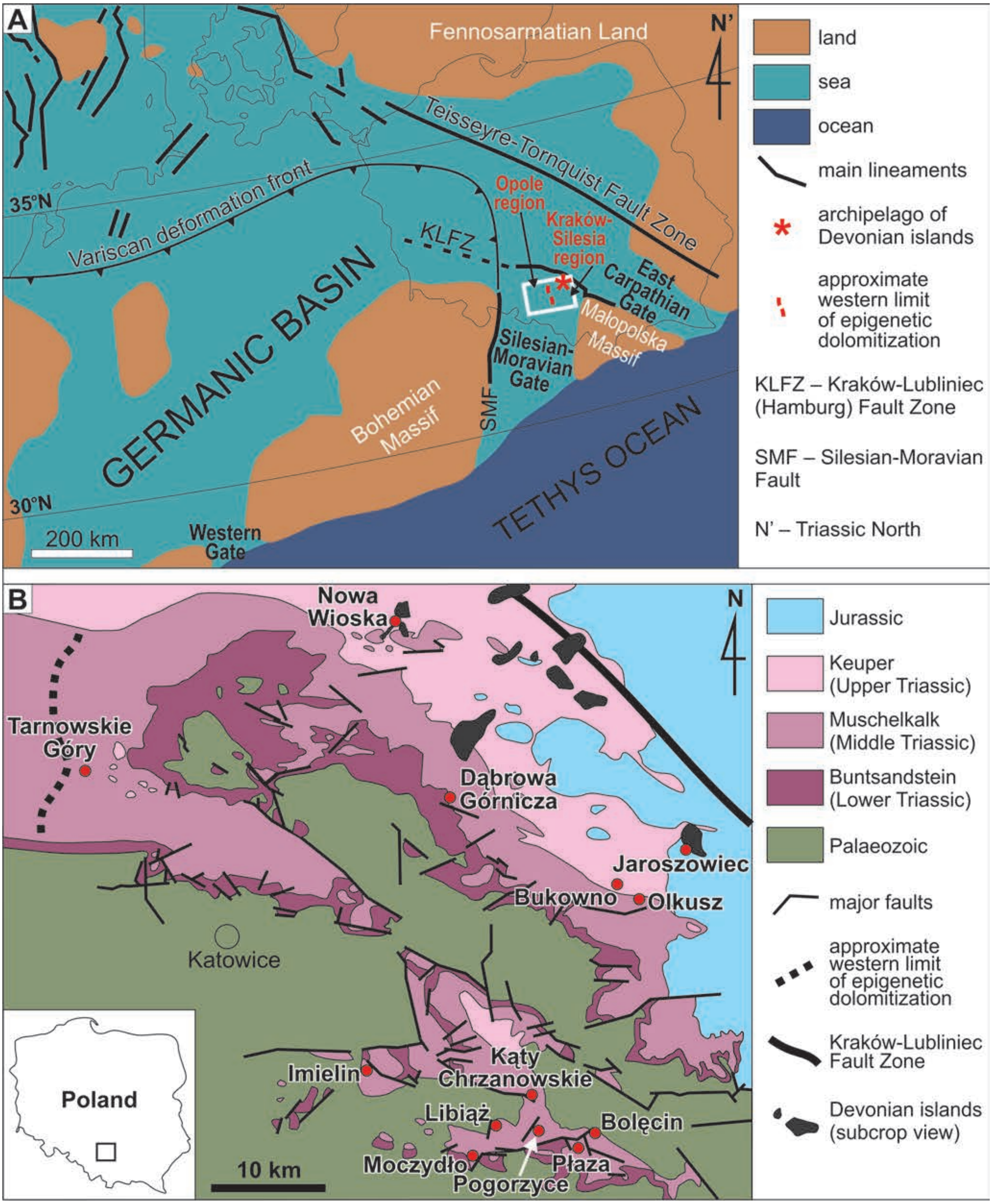


Fig. 1. Location of the study area. **A.** Palaeogeographic map of the Germanic Basin in the Middle Triassic. The Upper Silesia region (white rectangle) was situated close to the Tethys Ocean. Modified after Narkiewicz and Szulc (2004). **B.** Present outcrop distribution of the Middle Triassic (Muschelkalk) carbonates in the Kraków-Silesia (studied) region, and the position of the Kraków-Lubliniec Fault Zone and the Devonian islands in the subsurface. Simplified after Myszkowska (1992).

rzyński, 1979; Pawłowska, 1982, 1985; Wyczółkowski, 1982; Myszkowska, 1992). However, it should be stressed that the primary lithology was an important factor, controlling the flow of the dolomitizing fluids in late (burial) diagenesis and the emplacement of ore deposits in this horizon; for instance, the most ferruginous "ore-bearing dolomites" (called ankerites) are developed in the coarsest-grained peloidal grainstones (Śliwiński, 1962, 1964; Pomykała, 1975; M. Matysik, unpublished data, 2012), and major ore bodies occur just above the impermeable horizon of wavy-nodular clay-rich limestones (e.g., Gruszczyk, 1957; Śliwiński, 1962; Bogacz *et al.*, 1970). Bogacz *et al.* (1975) are the only authors to suggest that the hydrothermal solutions rose on a broad front along the faulted and folded NE margin of the Kraków-Silesia region and migrated from there to the SE, guided by sedimentary interfaces and porous primary dolostones. In accordance with this important interpretation, the facies heterogeneity within the "ore-bearing dolomite" succession should be investigated first, before any sound model of fluid circulation can be proposed.

Another problem, arising from the insufficient recognition of facies heterogeneity, is the ongoing confusion in the lithostratigraphic nomenclature. The "ore-bearing dolomite" interval is traditionally, but factitiously divided into three formations (informally also called "beds", see Figs 2, 3): the Górażdże Formation, the Dziewkowice Formation and the Karchowice Formation. Their names were simply adopted by Siedlecki (1948) from the pioneer lithostratigraphic scheme of Assmann (1913, 1944), proposed for the undolomitized Muschelkalk succession, cropping out to the west of the Kraków-Silesia ore district. This scheme was copied, despite the marked lithofacies differences in the two areas. Although several authors highlighted the problem of misuse of these unit names (Gruszczyk, 1956; Śliwiński, 1966a), and Śliwiński (1961) even introduced the term "Olkusz Beds" for the "ore-bearing dolomite" succession, stratigraphers and miners still apply the lithostratigraphic terms, which have no precise equivalents in the rock record of the Kraków-Silesia region.

This paper presents a detailed (bed-by-bed) sedimentological analysis of the Lower Muschelkalk succession and its lateral variability within the Kraków-Silesia region. On the basis of this large database, this paper also reconstructs step by step the evolution of this part of the Germanic Basin in the Anisian and shows which particular events contributed to the formation of the epigenetic "ore-bearing dolomite". The subordinate goal of this paper is to organize the lithostratigraphic scheme of the "ore-bearing dolomite" succession.

SEDIMENTARY ENVIRONMENT OF THE EPIGENETICALLY DOLOMITIZED UPPER SILESIAN MUSCHELKALK CARBONATES: A BRIEF REVIEW OF THE LITERATURE

In many earlier papers (e.g., Assmann, 1913, 1944; Siedlecki, 1948, 1952; Alexandrowicz and Alexandrowicz, 1960; Śliwiński, 1961, 1966a; Pastwa-Leszczyńska, 1962; Alexandrowicz, 1966, 1971, 1972), the sedimentary environment of the epigenetically dolomitized Triassic carbonates was not discussed at length, because lithostratigraphy was the main focus in those days. Later, Wyczółkowski (1971, 1982) succinctly described the influence of the pre-Triassic morphology on the sediment thicknesses and overall facies distribution in the Muschelkalk sea and also reconstructed the particular areas of the Kraków-Silesia region that were flooded during the subsequent, transgressive pulses. Pawłowska and Szuwarzyński (1979) and Pawłowska (1982, 1985) characterized for the first time the lithofacies types, carbonate grains, porosity, diagenetic alterations and sedimentary environment. They concluded that the "ore-bearing dolomite" succession generally represents a tidal-flat environment, but the lower part of the succession (corresponding approximately to the Górażdże Formation) was formed in the subtidal zone and the upper part (approximately the undifferentiated Dziewkowice–Karchowice formations), in the inter- and supratidal zones. Subtidal conditions returned to the area during deposition of the oncolites that are widely regarded as the bottom unit of the overlying Diplopora Beds (Fig. 3).

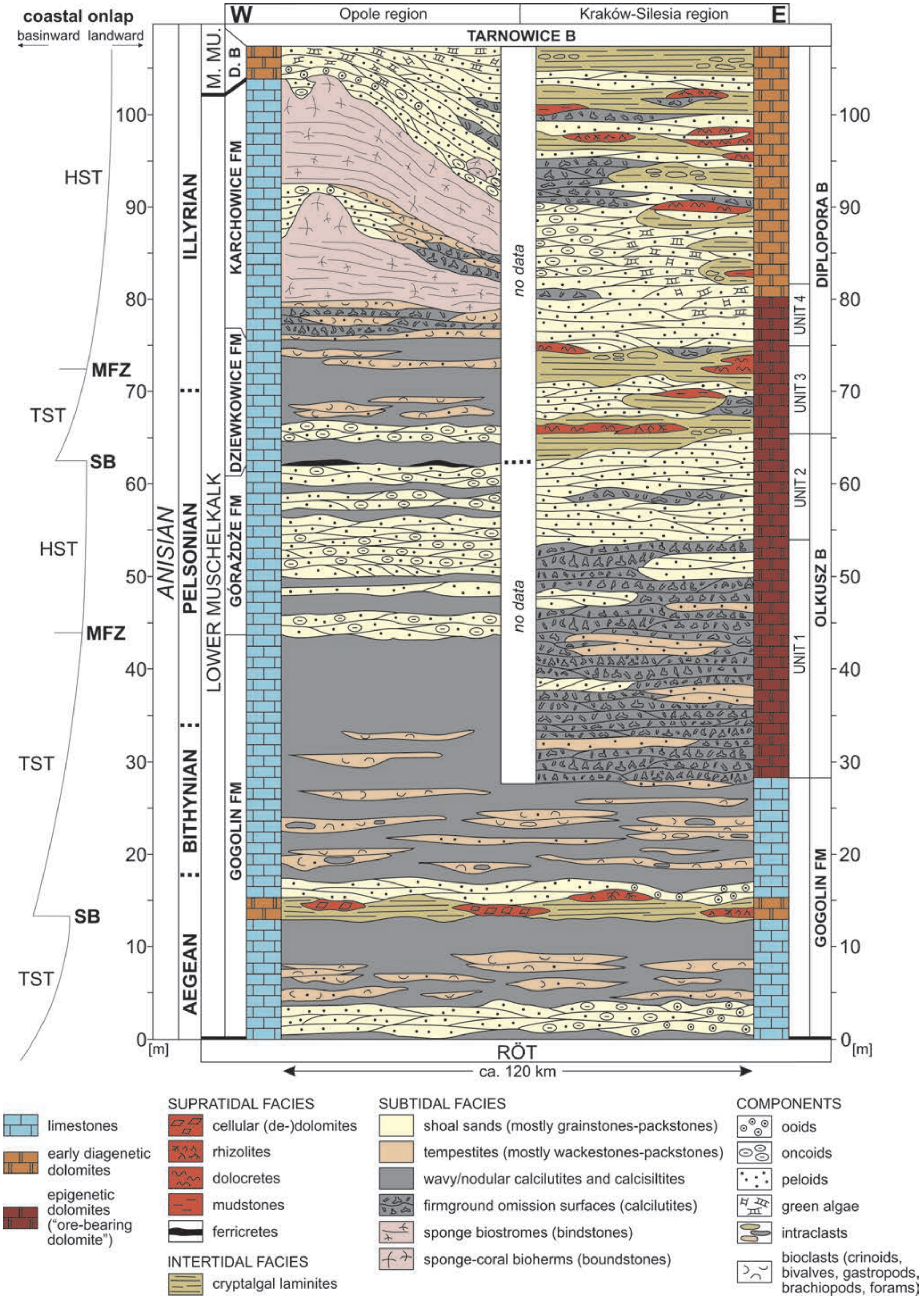
A further attempt to reconstruct the evolution of the Kraków-Silesia region in the late Anisian was undertaken by Myszkowska (1992). On the basis of lithological similarities, this author correctly included the undifferentiated Dziewkowice–Karchowice formations in the overlying Diplopora Beds and divided the latter into three distinct intervals representing different depositional settings. The lower complex (corresponding to the undifferentiated Dziewkowice–Karchowice formations) was built of carbonate mudstones, grapestones, peloidal packstones and microbial laminites with mudcracks and birdseyes, which represented low-energy, shallow lagoons and temporarily emerged areas. The middle complex, composed of crinoidal and green algal dolostones as well as oolites and oncolites, was deposited in a shallow marine, higher-energy setting. The upper complex commenced with carbonate muds, grapestones and peloidal packstones, formed in a calm, deeper environment, which upwards pass into oolites and microbial laminites, representing shallow agitated settings and emerged areas, respectively. Such a tripartite division of the Diplopora Beds is also used in the present study. However, several lithological features were not recognized by Myszkowska (1992).

GEOLOGICAL SETTING

The term "Upper Silesia" refers herein to the entire area of southern Poland, where Muschelkalk deposits crop out (Fig. 1A). Only in the eastern part of Upper Silesia, called "the Kraków-Silesia region", these deposits were affected by the epigenetic dolomitization and Pb-Zn mineralization. The western part, termed "the Opole region", does not show such dolomitization and mineralization.

Palaeogeography and tectonic framework

In the Middle Triassic, the semi-closed Germanic Basin was situated at subtropical latitudes (Ziegler, 1990; Go-


coastal onlap
basinward
landward
HST
MFZ
TST
SB
HST
MFZ
TST
SB
TST
W
Opole region
Kraków-Silesia region
E
TARNOWICE B
ANISIAN
ILLYRIAN
PELSONIAN
BITHYNIAN
AEGEAN
M. MU.
LOWER MUSCHELKALK
D. B
KARCHOWICE FM
DZIEWKOWICE FM
GÓRAŻDŻE FM
GOGOLIN FM
DIPLOPORA B
OLKUSZ B
UNIT 4
UNIT 3
UNIT 2
UNIT 1
GOGOLIN FM
no data
no data
100
90
80
70
60
50
40
30
20
10
0
[m]
RÖT
ca. 120 km
limestones
early diagenetic dolomites
epigenetic dolomites ("ore-bearing dolomite")
SUPRATIDAL FACIES
cellular (de-)dolomites
rhizolites
dolocretes
mudstones
ferricretes
INTERTIDAL FACIES
cryptalgal laminites
SUBTIDAL FACIES
shoal sands (mostly grainstones-packstones)
tempestites (mostly wackestones-packstones)
wavy/nodular calcilutites and calcisiltites
firmground omission surfaces (calcilutites)
sponge biostromes (bindstones)
sponge-coral bioherms (boundstones)
COMPONENTS
ooids
oncoids
peloids
green algae
intraclasts
bioclasts (crinoids, bivalves, gastropods, brachiopods, forams)

lonka, 2002; Scotese 2003). Communication with the Tethys Ocean was provided by three fault-controlled seaways, called “gates” (Fig. 1A). This configuration determined the specific overall “Germanic facies” distribution throughout the basin with normal-marine settings prevailing near the gates, and more restricted environments occurring in the central-to-marginal basin areas (Szulc, 2000). On a smaller scale, however, the basin was filled in a more complex and diverse way, reflecting the unpeneplained post-Variscan topography (Wyczółkowski, 1971, 1982) and syndepositional block tectonics (Szulc, 1989). The Upper Silesian Sub-basin, located close to the Silesian-Moravian Gate, dipped to the west. The western part of it (the Opole region) was dominated by subtidal facies even during highstands (Szulc, 2000), whereas the eastern part (the Kraków-Silesia region) belonged temporarily to the inter- and supratidal zones (Pawłowska and Szuwarzyński, 1979; Pawłowska, 1982, 1985; Myszkowska, 1992).

The Małopolska Land bordered the Kraków-Silesia region to the SE, but its shore facies is nowhere exposed. The Małopolska Land passed to the NW into an archipelago of several isolated, irregularly scattered, cliff-edged islands, made up of Devonian carbonates. These represent areas of Variscan uplift (Fig. 1B), characterized by differences in size and geometry (Śliwiński, 1966a; Wyczółkowski, 1971, 1982). Intensive erosion of the cliff walls produced a large amount of millimetre- to decimetre-size lithoclasts, most of which were deposited up to 50 m from the island margins (Alexandrowicz, 1971; Wyczółkowski, 1971, 1982). The islands formed an elongate belt, 30 by 15 km in size, stretching along the Kraków-Lubliniec Fault Zone (KLFZ). The KLFZ is regarded as the place of accretion of two different tectonostratigraphic units, called the Brunovistulikum Terrane and the Małopolska Terrane (Żaba, 1999; Buła *et al.*, 2008). Although the accretion took place in the early Palaeozoic, the KLFZ also was active later. The Variscan Orogeny caused intense deformation of the KLFZ, including considerable vertical displacement of several tectonic blocks, namely the cliff islands mentioned above (Śliwiński, 1966a; Wyczółkowski, 1971, 1982). The Mesozoic activity of the KLFZ resulted in synsedimentary tectonic deformation of the accumulated sediments (Szulc, 1989, 2000); seismic pumping of hydrothermal fluids also is assumed to have occurred (Heijlen *et al.*, 2003).

Stratigraphy

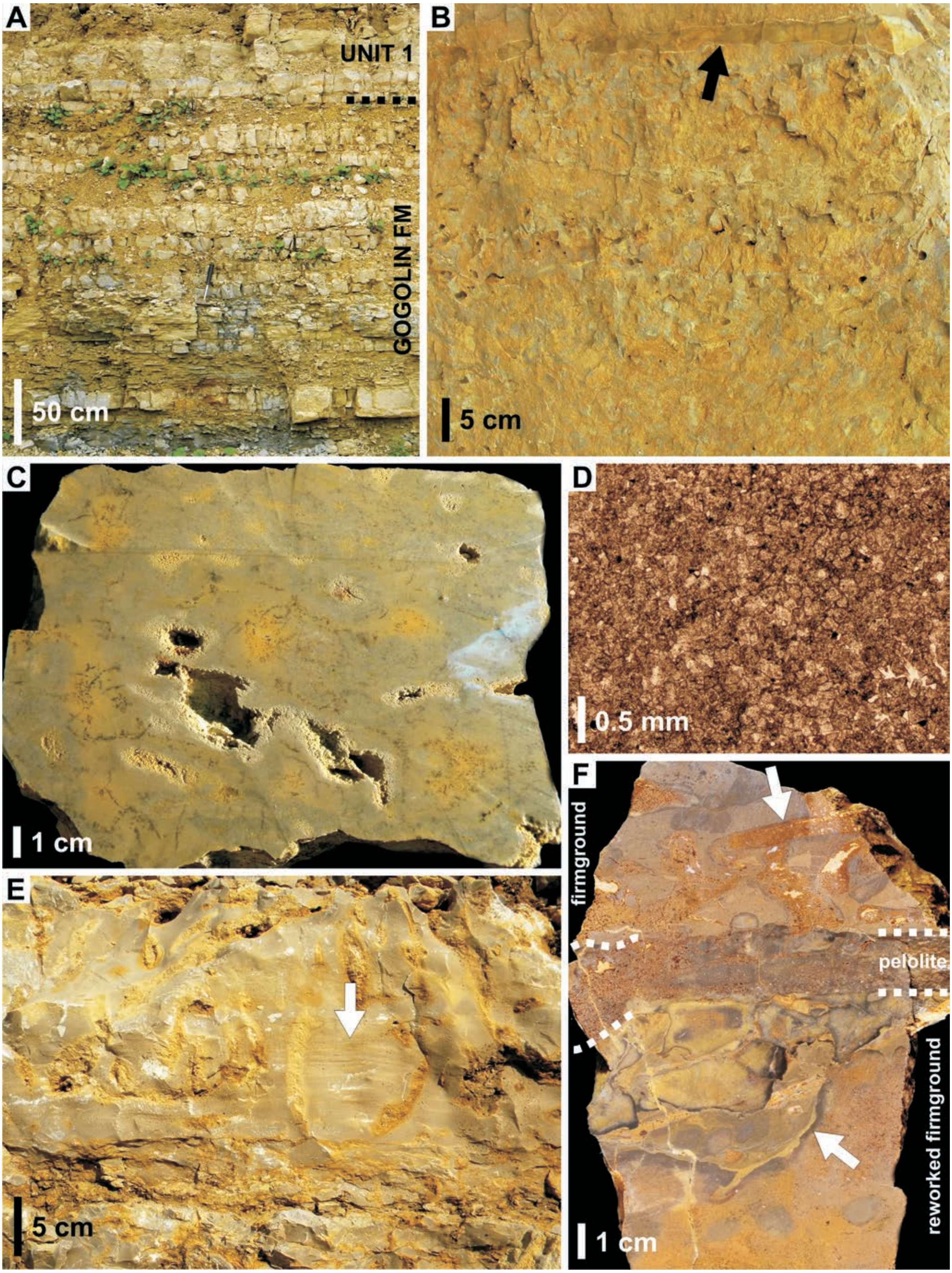
The evolution of the Upper Silesian Sub-basin in the Middle Triassic was strongly influenced by third-order sea-level fluctuations, superimposed on the differential basin morphology (Wyczółkowski, 1982; Szulc 2000). Whereas changes in accommodation space generated long-term vertical facies changes, the topography determined the lateral facies distribution in particular time intervals. Accordingly, the sedimentary succession of the Kraków-Silesia region differs markedly from the succession of the Opole region. These differences (and similarities) are summarized in Fig. 3. While simple lithostratigraphic correlation cannot be applied, both successions are well correlated with each other and with the Tethys domain by magnetostratigraphy (Nawrocki and Szulc, 2000), sequence stratigraphy (Szulc, 2000) as well as conodont, ammonoid and crinoid biostratigraphy (Assmann, 1944; Zawidzka, 1975; Hagdorn and Głuchowski, 1993; Kaim and Niedźwiedzki, 1999; Narkiewicz and Szulc, 2004). According to these data, the “ore-bearing dolomite” interval is Pelsonian–Illyrian (upper Anisian) in age (Fig. 3).

Horizontal and vertical range of the ore-bearing dolomite

The ore-bearing dolomite occupies an area of 50 by 30 km. It is delimited north–eastwards by the KLFZ, westwards by the dislocation running N–S near Blachówka, and southwards by post-Triassic erosion (Fig. 1B; Assmann, 1926, 1944; Śliwiński, 1961). Stratigraphically, the stratiform body of ore-bearing dolomite, approximately 35 m thick, overlies the wavy-nodular clay-rich limestones of the Gogolin Formation (Fig. 3), which formed an impermeable barrier to hydrothermal fluid flow, migrating downward owing to gravitation (e.g., Bogacz *et al.*, 1970). In contrast, the upper limit of epigenetic dolomitization is discordant with the lithostratigraphy and therefore it cannot be identified as one distinct surface of lithological change. All earlier authors misidentified the upper limit of dolomitization as the bottom of the Diplopora Beds, but in fact the attributes, characteristic for the ore-bearing dolomite (the colour range of oxidised iron, dolomitized texture and/or common dissolution vugs), disappear several metres above the bottom of the Diplopora Beds (Fig. 3).

The ore-bearing dolomite contains metre- to kilometre-size relics of the primary facies of the Muschelkalk limestones (Bogacz *et al.*, 1972; Sobczyński and Szuwarzyński, 1974; Mochnacka and Sass-Gustkiewicz, 1978), which can be studied today in only a few places. Furthermore, where major dislocations cross each other, the epigenetic dolomitization affected also the Devonian to Jurassic strata (e.g., Ekiert, 1957; Gałkiewicz *et al.*, 1960; Pałys, 1967; Górecka, 1993). For additional information on the dolomitization and mineralization processes in the region, interested readers are referred to the primary literature (e.g., Ekiert, 1957; Grusz-

Fig. 3. Generalized stratigraphic section for the Lower–Middle Muchelkalk of Upper Silesia, showing thickness, overall lithological character, provisional formation names and range of epigenetic dolomitization. M. MU. – Middle Muschelkalk; D. B – Diplopora Beds; TST – transgressive systems tract; HST – highstand systems tract; MFZ – maximum flooding zone; SB – sequence boundary. Sequence stratigraphy framework after Szulc (2000), lithostratigraphy of the Opole region after Assmann (1913, 1944) with later formalization by Bodzioch (1997), Niedźwiedzki (2000) and Kowal-Linka (2008).


A
UNIT 1
GOGOLIN FM
50 cm
B
5 cm
C
1 cm
D
0.5 mm
E
5 cm
F
firmground
pelolite
reworked firmground
1 cm

czyk, 1957; Gałkiewicz *et al.*, 1960; Śliwiński, 1962, 1964; Harańczyk, 1965; Pałys, 1967; Smolarska, 1968; Górecka, 1970; Bogacz *et al.*, 1970, 1972, 1975; Zartman *et al.*, 1979; Gruszczyk and Strzelska-Smakowska, 1978; Kozłowski *et al.*, 1980; Szuwarzyński, 1983, 1996; Harańczyk, 1983; Wodzicki, 1987; Górecka, 1996; Leach *et al.*, 1996a, b; Viets *et al.*, 1996; Sass-Gustkiewicz and Dżułyński, 1998; Heijlen *et al.*, 2003; Coppola *et al.*, 2009).

MATERIALS AND METHODS

Out of several tens of investigated outcrops, only the most interesting and complete sections were presented. These are outcrops, where the macrotextural features were affected by epigenetic dolomitization to only a minor extent, and consequently sedimentary structures or changes in grain size could be recognized. All sections, in which dolomitization obliterated sedimentary structures completely or made it impossible to distinguish carbonate muds from grains, were excluded. By courtesy of the “Olkusz-Pomorzany” lead-zinc mine, three drill cores from the vicinity of the mine were examined. Most of the core intervals were not slabbed, and therefore the measured lithostratigraphic logs may contain mistakes. For the GPS coordinates of each outcrop, see the Appendix.

Field studies were completed with the analysis of about 900 polished slabs and 400 thin sections. It should be stressed that much of the original rock microtexture had been destroyed as a result of epigenetic dolomitization, which significantly limited microfacies description and interpretation. On the other hand, the ubiquitous silica nodules turned out to be a very useful tool in microfacies analysis, because silification protected the primary microtextures from epigenetic changes. The origin of the chert nodules was described in detail by Kwiatkowski (2005).

For the most complete sections, exhibiting plenty of sedimentary structures, circular histograms (rose diagrams) were constructed to present the frequency distributions of inferred local directions of sediment transport (Potter and Pettijohn, 1963; Nemec, 1988). The histograms were created in the following way: 1) each layer, displaying unidirectional cross-bedding, was counted as one azimuth measurement (m1); 2) if the top of a layer was shaped by symmetrical ripples or dunes (bidirectional sedimentary structures), two azimuth measurements were counted (m1 and m2), both perpendicular to the orientation of ripple/dune crests (r1) but each the reverse of the other (m1 = r1 + 90° and m1 = r1 – 90°); 3) planar-bedding and hummocky cross-stratified beds were not counted. The histograms include corrections suggested by Nemec (1988), namely that the area of each circular sector of the rose diagram, not the radius of the sector, is proportional to the class frequency (density).

With respect to the geological terminology, “pelolite” is a carbonate rock composed predominantly of peloids (by analogy to oolite and oncolite), independently of whether it had been a limestone or early diagenetic dolomite, prior to epigenetic dolomitization.

SEDIMENTARY SUCCESSION OF THE “ORE-BEARING DOLOMITE”

The succession of the ore-bearing dolomite consists of four distinct lithostratigraphic intervals, representing different phases in the evolution of the Kraków-Silesia Sub-basin. Each interval displays lateral variation in thickness and sedimentary features (Figs 2, 3). These basic lithostratigraphic units fulfill the recent definition of “Member” (see North American Commision on Stratigraphic Nomenclature, 2005; Narkiewicz, 2006). However the definition of formal divisions is beyond the scope of this paper.

Unit 1

Unit 1 constitutes the lower half of the Olkusz Beds (*sensu* Śliwiński, 1961; Figs 2, 3).

Lower boundary

Unit 1 directly overlies the topmost part of the Gogolin Formation, composed of wavy-nodular clay-rich calcilutites with ubiquitous horizontal trace fossil *Rhizocorallium* isp., infilled with coprolites (Fig. 4A). These calcilutites in places are interbedded with centimetre-thick bioclastic wackestones-packstones and hummocky cross-stratified calcisiltites.

Description

Unit 1 is predominantly composed of medium-bedded (10–30 cm), red-brown-grey cavernous dolosiltites with irregularly disseminated spots, which exhibit fine-crystalline texture in thin sections (Figs 2, 4B–D). The primary lithological features of these deposits are well preserved in several sections, which escaped the epigenetic dolomitization.

◄

Fig. 4. Main lithological features of Unit 1. **A.** General view of the transition from the wavy-nodular clay-rich calcilutites (the uppermost part of the Gogolin Formation) to the medium-bedded firmgrounds of Unit 1. Imielin – “PPKMiL” Quarry. **B.** Vertical outcrop view of cavernous spotty dolostone. Black arrow points at flat silica nodule. Imielin – “PPKMiL” Quarry. **C.** Vertically oriented slab of cavernous spotty dolostone. Note that coarse-grained infilling of burrows was dissolved, which resulted in development of vugs. Dąbrowa Górnicza – “Ząbkowice” Quarry. **D.** Microphotograph of C, illustrating fine-crystalline texture. **E.** Vertical outcrop view of undolomitized firmground horizon with burrows ?*Balanoglossites*. Note the parallel lamination preserved in some places (white arrow). Płaza – “GiGa” Quarry. **F.** Vertically oriented slab of two firmground horizons, separated by ?tempestitic pelolite. Lower firmground horizon is reworked to form a conglomerate. White arrows indicate diagenetic haloes formed around burrows (due to mucus-impregnation). Note that only the coarse-grained infilling of the burrows was altered (recolouration and crystal change) during epigenetic dolomitization, whereas the fine-grained sediment around burrows did not undergo epigenetic changes. Imielin – “PPKMiL” Quarry.

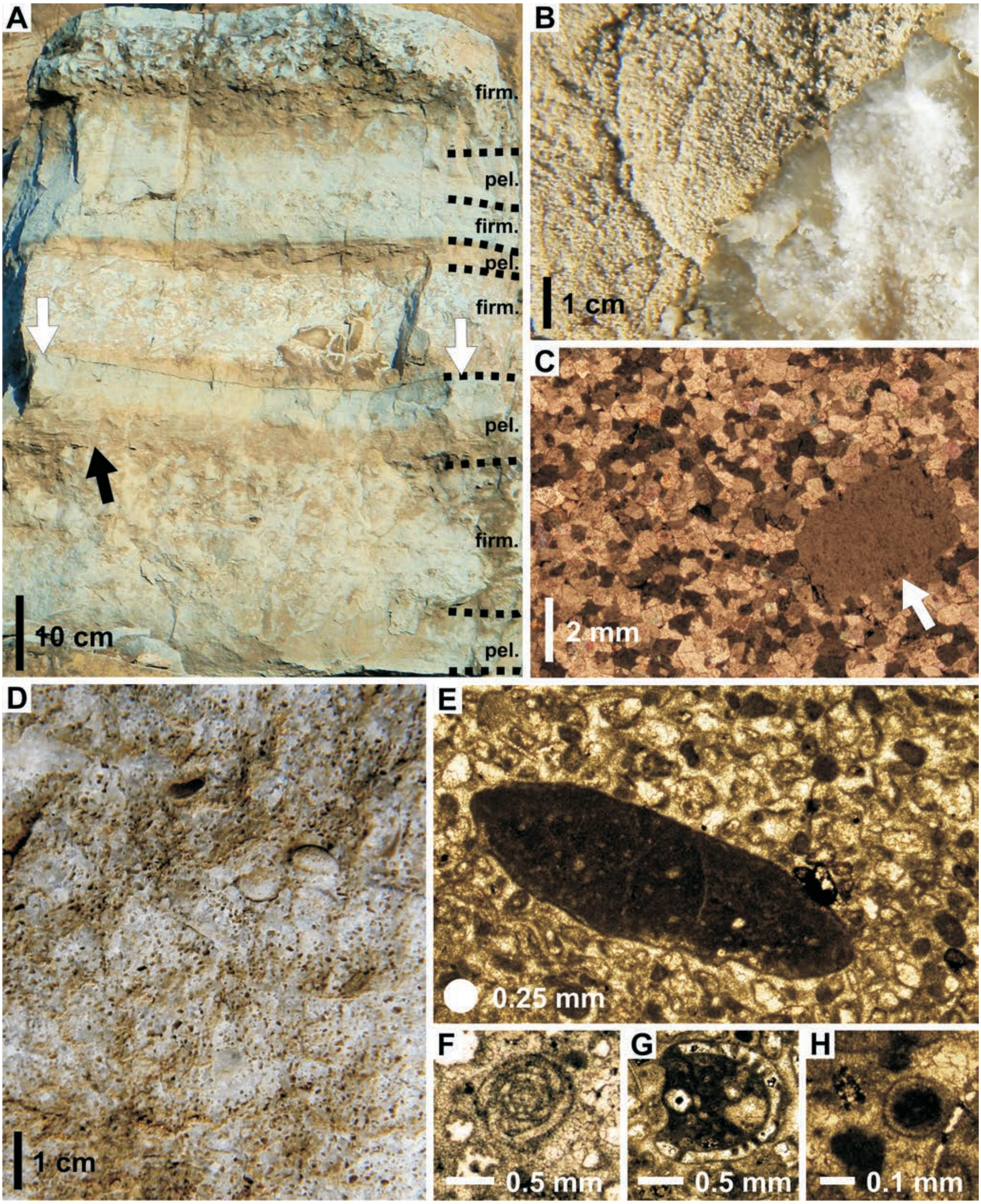


Fig. 5. Main lithological features of Unit 1. **A.** Vertical outcrop view of several firmground horizons (firm.; spotty dolostones with some caverns) sandwiched in between pelolites (pel.). Some pelolites display hummocky cross-stratification (black arrow). White arrows indicate hummocks. Pogorzyce – "Żelatowa" Quarry. **B.** Vertical outcrop view of silicified (on right side) and unsilicified (on left side) fine-grained peloidal packstone-grainstone. Imielin – abandoned quarry. **C.** Photomicrograph of pelolite, showing coarse-crystalline microtexture enclosing the crinoid ossicle (white arrow). Note that the ossicle margins were dissolved and replaced by dolomite crystals. X nicols. Pogorzyce – "Żelatowa" Quarry. **D.** Vertical outcrop view of undolomitized peloidal grainstone, displaying moldic porosity and containing sporadic bivalves. Olkusz Stary – abandoned quarry. **E–H.** Photomicrographs of D. **E.** Peloidal grainstone with rounded micritic intraclast. Many peloids are dissolved. **F.** Foram test. **G.** Cross-section of green algae. **H.** Peloid with thin ooidal cortex.

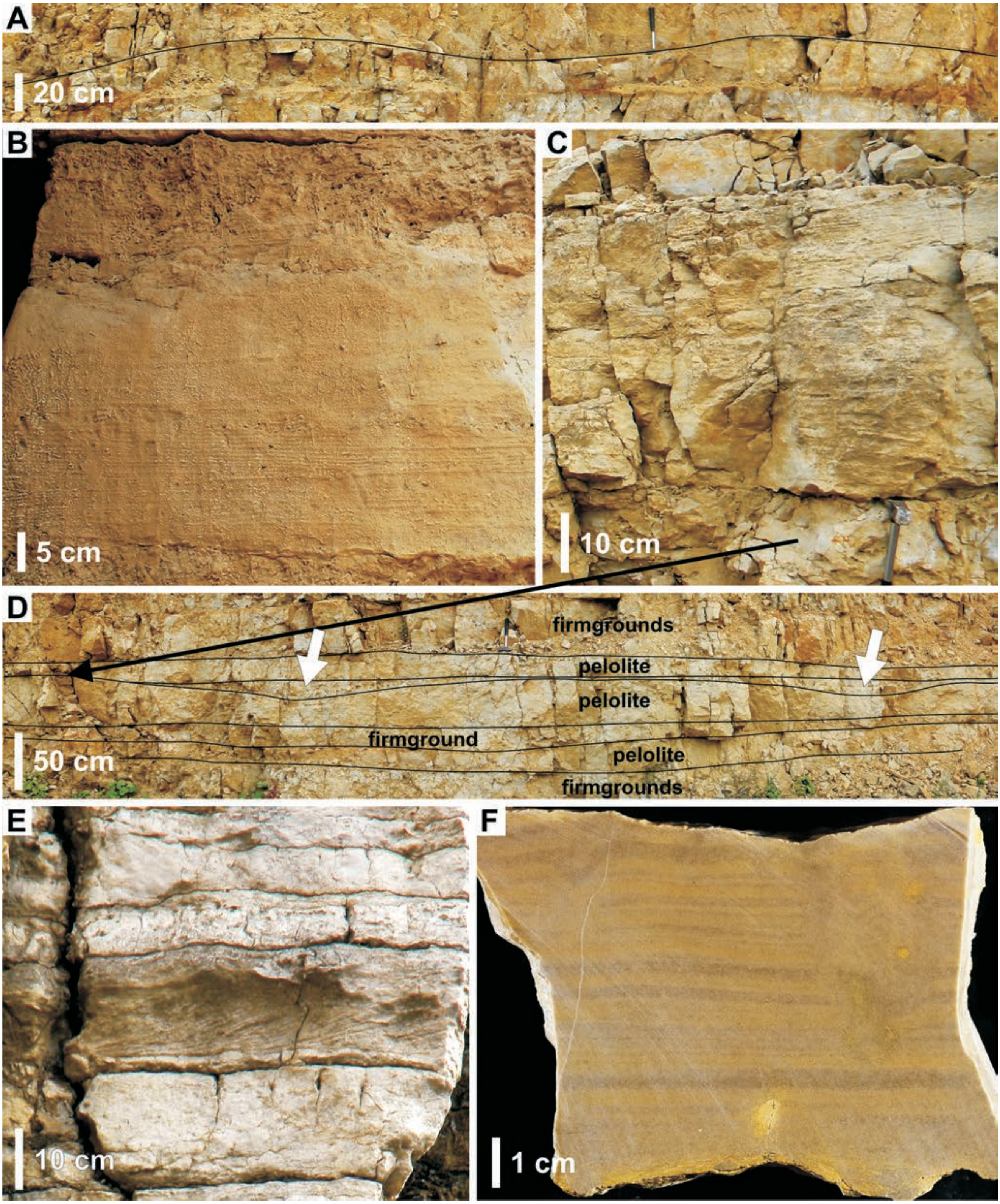
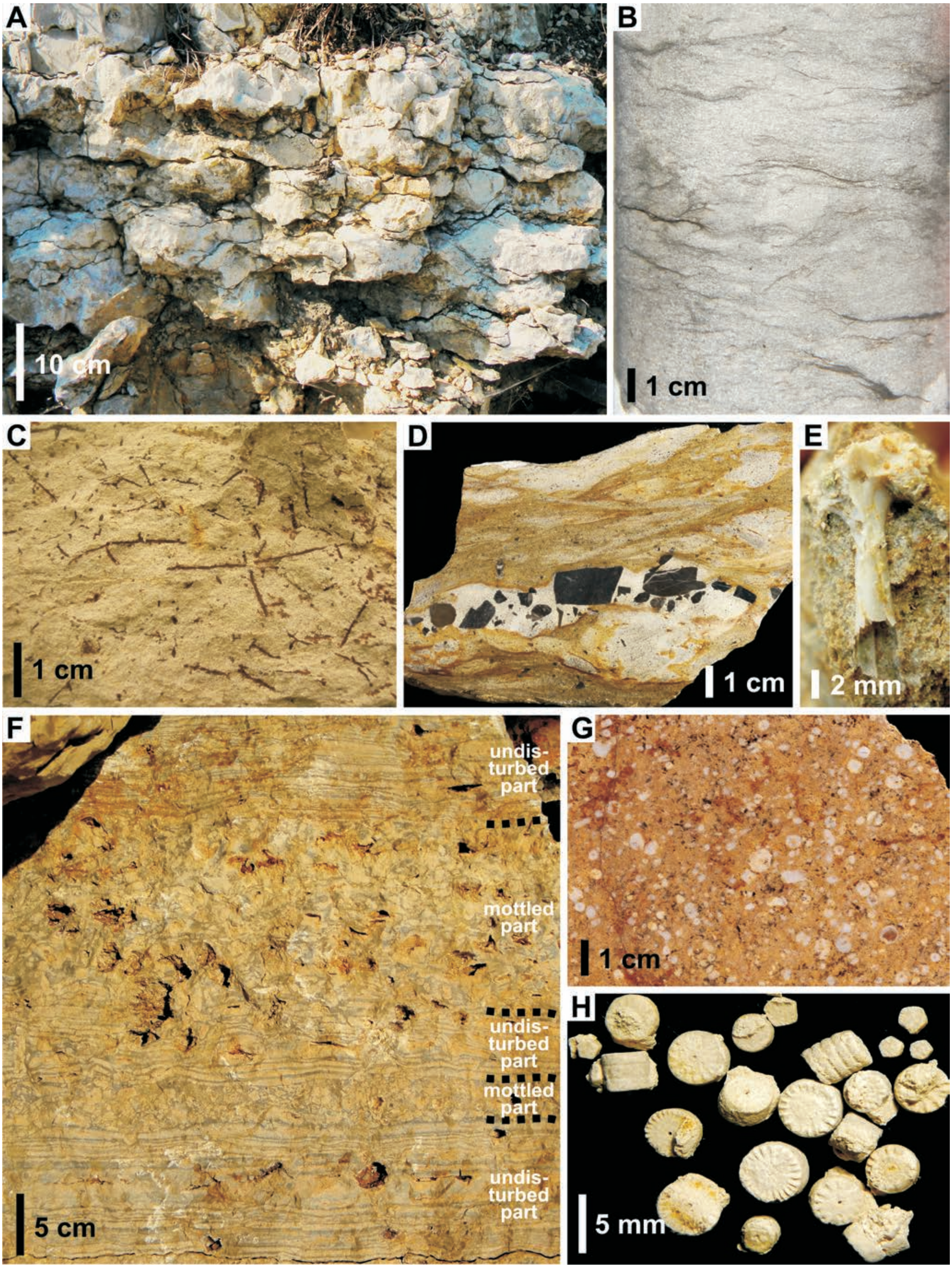


Fig. 6. Sedimentary structures of Unit 1. **A.** Vertical outcrop view of large-scale hummocks. Dąbrowa Górnicza – "Ząbkowice" Quarry. **B.** Vertical outcrop view of dolomitized hummocky cross-stratified pelolite, overlain by firmground. Note several truncated low-angle laminae sets diagnostic of hummocky cross-stratification. Dąbrowa Górnicza – "Ząbkowice" Quarry. **C–D.** Vertical outcrop views of several dolomitized large-scale cross-stratified peloidal dunes, sandwiching firmgrounds. Note laterally discontinuous firmground horizon (white arrows) and resultant amalgamation of two dunes. Dąbrowa Górnicza – "Ząbkowice" Quarry. **E.** Vertical outcrop view of undolomitized pelolite, displaying high-angle (tabular) cross-bedding with tangential relationship to the basal surface. Olkusz Stary – abandoned quarry. **F.** Vertically oriented slab of undolomitized laminated fine-grained pelolite. Lamination is slightly disturbed by bioturbation. Płaza – "GiGa" Quarry.


A
10 cm
B
1 cm
C
1 cm
D
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E
2 mm
F
undis-
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mottled
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part
mottled
part
undis-
turbed
part
5 cm
G
1 cm
H
5 mm

These are dark grey laminated unfossiliferous calcilutites, with burrows *Balanoglossites* and *Thalassinoides* (firmground omission surfaces). Parallel lamination was often obliterated by bioturbation (Fig. 4E). The burrows are commonly surrounded by a black diagenetic halo, which gradually fades away from the burrow wall (Fig. 4F). The burrows are infilled either with fecal pellets or yellow detrital sediment, composed of micrite, peloids and sporadic disarticulated bivalves. Blocky calcite crystallized in remnant open voids of burrows. The firmgrounds were sometimes destroyed by submarine erosion to form conglomerates with subrounded pebbles (Fig. 4F).

The firmgrounds are intercalated with medium-bedded pelolites. Epigenetically dolomitized pelolites are red-brown in colour and display medium- to coarse-crystalline microtexture (Fig. 5A–C). They contain disarticulated crinoids and steinkerns of bivalves and gastropods. Undolomitized pelolites permit more detailed description. These are white calcisiltites and fine- to medium-grained calcarenites (termed “crystal” by Siedlecki, 1948; 1952), usually packstones-grainstones and rarely wackestones (Fig. 5D, E). Their main constituents are moderately rounded and sorted peloids, some of which have very thin ooidal cortex (Fig. 5H). Crinoids, bivalves, brachiopods, gastropods, green algae, forams and grey flat micritic pebbles were identified as accessory components (Fig. 5E–G). Many peloids and bioclasts, except for crinoids, are dissolved (moldic porosity).

Whether dolomitized or not, pelolites have clearly visible sedimentary structures and they form single beds or amalgamated packages. Single pelolitic beds reach up to 50 cm in thickness (mostly 10–30 cm), whereas the amalgamated pelolitic packages have usually 0.5–1 m thickness (with a minimum of 10 cm and a maximum of 2 m). Both display various sedimentary structures: planar and low-angle lamination, hummocky cross-stratification with hummocks up to 5 m across, tabular cross-bedding, symmetrical ripples 20–40 cm long and 3–8 cm high, as well as dunes 0.6–10 m long and 5–30 cm high (Fig. 6A–E). The ripple and dune crests run generally NE–SW, while the cross-laminae dip dominantly in two opposite directions: from N to W and from S to E (Fig. 2). Vertical burrows occasionally cut the pelolites, especially where they directly underlie firmgrounds with intensive bioturbation (Fig. 6F).

The thickness and abundance of pelolites increase stratigraphically upwards. This feature is most clearly visible at Imielin (Fig. 2).

Lateral variability

The firmgrounds that predominate in Unit 1 locally give way to nodular calcilutites-calcisiltites with unidentifiable horizontal trace fossils (Płaza, Olkusz Stary; Fig. 7A), or to flaser-laminated dolosiltites (Bukowno; Fig. 7B). In the vicinity of the Devonian islands, the firmgrounds are partially replaced by vertebrate-bearing dolocretes, rhizolites and poorly sorted cliff-breccias to cliff-dolosiltites (Jaroszowiec, Nowa Wioska; Fig. 7C–E), or by cavernous unfossiliferous wavy- to planar-bedded dolostones (Nowa Wioska; Fig. 7F). The latter are made up of alternating 1-cm-thick layers of grey dolosiltite and yellow peloidal dolarenite, which are frequently affected by bioturbation and occasionally cut by erosional channels (1 m wide and 30 cm deep).

The pelolites are also characterized by a marked lateral variability. In the most western sections (Tarnowskie Góry), the pelolites constitute only sporadic intercalations within succession of dolomitized firmgrounds, at least 32 m thick, and contain significant amounts of disarticulated crinoids (Fig. 7G, H). Similarly, the pelolites are almost absent from the easternmost sections, located within the archipelago of Devonian islands (Nowa Wioska, Jaroszowiec). At Imielin, in contrast, the pelolites form exceptionally thick grainstone bodies (up to 2 m in thickness), displaying trough cross-bedding. They are sometimes penetrated by vertical, straight or U-shaped burrows, resembling *Skolithos* isp. and *Arenicolites* isp., respectively. The lack of pelolites in the vicinity of the “Olkusz-Pomorzany” Mine should be attributed to the limited possibilities for observation in drill cores, rather than to any real absence of pelolites.

The thickness of Unit 1 is laterally variable. In most sections it ranges from 10 to 15 m. However, at Dąbrowa Górnicza it barely reaches 7 m, while at Imielin it is almost 20 m thick, and at Tarnowskie Góry at least 32 m (Fig. 3).

Interpretation

The lateral variability of Unit 1 described above (Fig. 2) indicates that the Kraków-Silesia Sub-basin was bathymetrically differentiated in the time interval discussed. Apparently, the proximal zone was established near the archipelago of Devonian islands, the medial zone occupied the broad central part of the Sub-basin, and the distal zone occurred at the western flank of the Sub-basin.

The proximal zone apparently was dominated by sedimentation in a tidal flat system, encompassing salt marshes and emerged areas. This is evidenced by rhizolites and dolocretes, respectively. Locally occuring wavy- to planar-bedded dolostones, composed of alternating layers of dolosil-

Fig. 7. Regional lithological changes within Unit 1. **A.** Vertical outcrop view of nodular calcisiltites. Olkusz Stary – abandoned quarry. **B.** Vertically oriented slab of flaser-laminated dolostone. Bukowno – “Olkusz-Pomorzany” Mine. **C.** Vertical outcrop view of a rhizolite with small straight root casts. Jaroszowiec – “Stare Gliny” Quarry. **D.** Vertically oriented slab of nodular dolocrete, containing black lithoclasts of Devonian dolostones. Jaroszowiec – “Stare Gliny” Quarry. **E.** Close view of nodular dolocrete, containing a bone fragment. **F.** Vertical outcrop view of wavy- to planar-bedded dolostones. Some bedsets were extensively bioturbated. Nowa Wioska – “PROMAG” Quarry. **G.** Vertically oriented slab of dolomitized pelolite, containing abundant crinoid ossicles. Tarnowskie Góry – “Blachówka” Quarry. **H.** Detail of G. Crinoid columns and ossicles, extracted from the rock. They are indicative of the late Anisian (Illyrian) silesiacus Biozone.

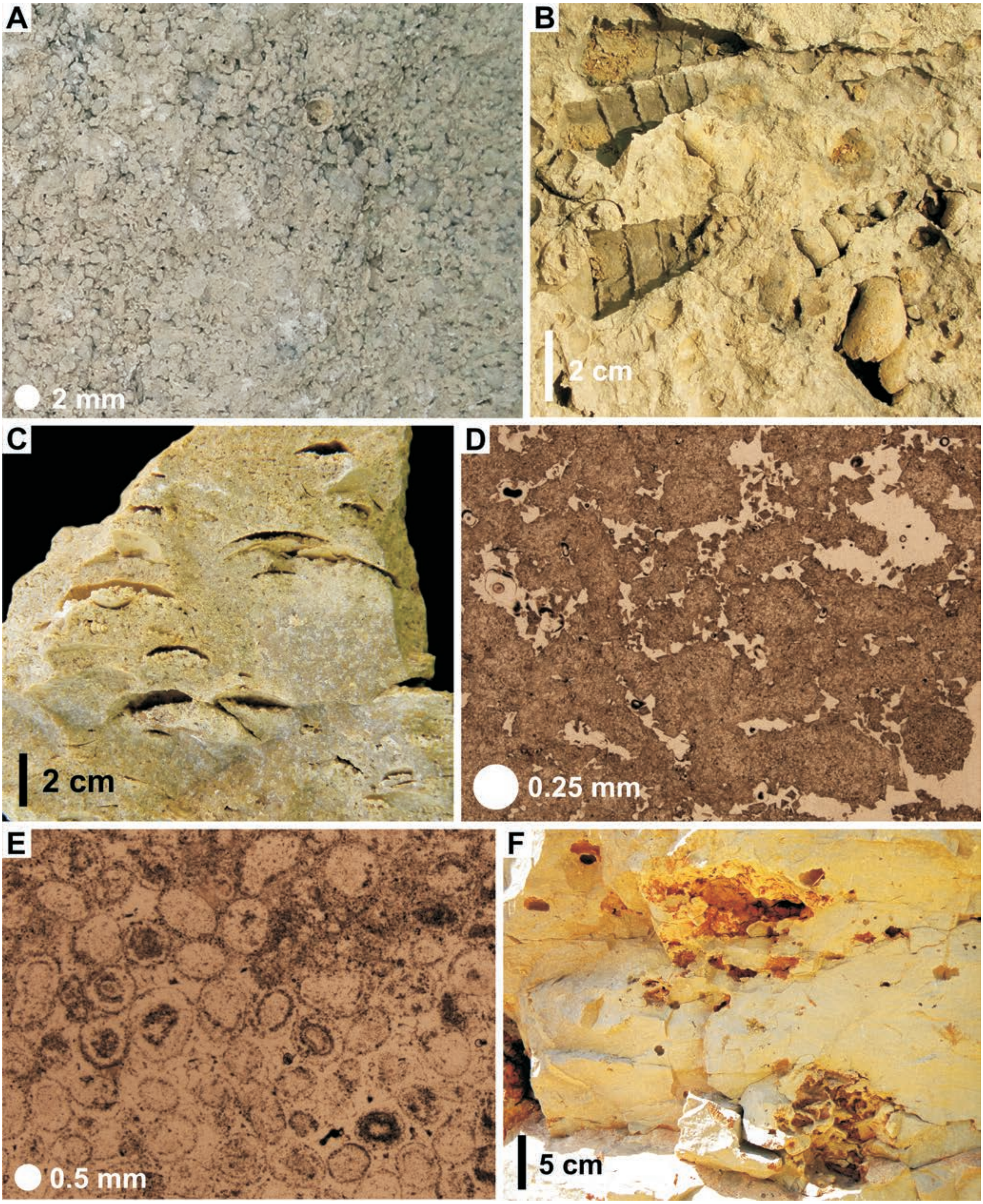


Fig. 8. Main lithological features of Unit 2. **A.** Bedding plane view of dolomitized coarse-grained peloidal grainstone. Bukowno – "Olkusz-Pomorzany" Mine. **B.** Bedding plane view of dolomitized pelolite, containing steinkerns of large gastropods. Imielin – "PPKMiL" Quarry. **C.** Vertical outcrop view of dolomitized pelolite, comprising voids after dissolved bivalve shells, aligned parallel to bedding planes and oriented convex-up. Nowa Wioska – "GZD" Quarry. **D.** Photomicrograph of pelolite, showing partially recrystallized microtexture of peloidal grainstone. Peloids are well rounded and moderately sorted. Pogorzyce – "Żelatowa" Quarry. **E.** Photomicrograph of silicified ooidal grainstone. Imielin – "PPKMiL" Quarry. **F.** Vertical outcrop view of large sparse cavernous vugs, developed within dolomitized fine-grained pelolite. Nowa Wioska – "GZD" Quarry.

tites and dolarenites, 1 cm thick, are very similar to wavy-, flaser- and lenticular-bedded deposits of tidal origin (e.g., Reineck and Singh, 1980; Demicco, 1983; Pratt and James, 1986) and are therefore interpreted as intertidal deposits. This interpretation is further supported by the lack of skeletal fossils and the presence of abundant burrows, probably created as shelter during the ebb tide. Owing to intensive cliff erosion, the close proximity of the islands is indicated by millimetre- to decimetre-sized lithoclasts of Devonian dolostone, accumulated as poorly sorted breccias, dolarenites and dolosiltites. It is clear that vertebrates inhabited this environment, since vertebrate bones were found both in cave-filling sediments (Lis and Wójcik, 1960) and in facies, formed adjacent to cliffs.

In the medial zone, including most of the sections studied, much of the sedimentation occurred under open-marine low-energy conditions, as indicated by the predominant firmground facies. The homogenously laminated structure of the firmgrounds, lacking internal erosional surfaces, implies that the carbonate mud was deposited from suspension as single events, presumably after storms (Matysik, 2010). Subsequent development of a firmground omission surface required a prolonged time span in the absence of sedimentation. Firmgrounds are also known to occur in other regions of the Germanic Basin, such as the Holy Cross Mountains, Poland (Kaźmierczak and Pszczółkowski, 1969), the Opole region, Poland (Bodzioch, 1989; Szulc, 2000; Matysik, 2010), and Thuringia, Germany (Knaust, 1998; Bertling, 1999). The pelolitic intercalactions between firmgrounds seem to have been mainly of storm origin, because: 1) most occur as single beds within an overall mud-dominated interval; and 2) some exhibit the hummocky cross-stratification, diagnostic of tempestites (Fig. 2; Harms *et al.*, 1975; Kreisa, 1981; Walker, 1982; Aigner, 1985; Duke, 1985). Those pelolites, which also form single beds, but display tabular cross-bedding or dunes, must have been deposited by unidirectional, relatively strong, but short-lived currents. Thick amalgamated packages of pelolites (known e.g., from Imielin), characterized by various large-scale sedimentary structures, including trough cross-beds, were apparently formed at depths above the normal wave-base. The medial zone generally represents the lower shoreface, affected by unidirectional currents, locally evolving into high-energy shoals. The composition of the pelolites suggests that the material came from two different sources. While crinoids, brachiopods and forams may be considered as an autochtonous, open-marine fauna reworked by storms, the bulk of the coarse-grained material, including peloids, gastropods, green algae and bivalves, must have been delivered from shallower areas of carbonate production, situated certainly eastwards or forming local short-term highs, such as at the Imielin site. The general increase in thickness and abundance of pelolite intercalations within the succession indicates the gradual shallowing of the medial zone through time.

The distal zone is also interpreted as representing the lower shoreface, although it was separated considerably from the influx of shoal material. Rare pelolite intercalations, rich in disarticulated crinoids and lacking other skeletal fossils, confirm the presence of more open-marine conditions, in comparison with the medial zone (Fig. 2).

Unit 2

Unit 2 constitutes the upper half of the Olkusz Beds (*sensu* Śliwiński, 1961; Figs 2, 3).

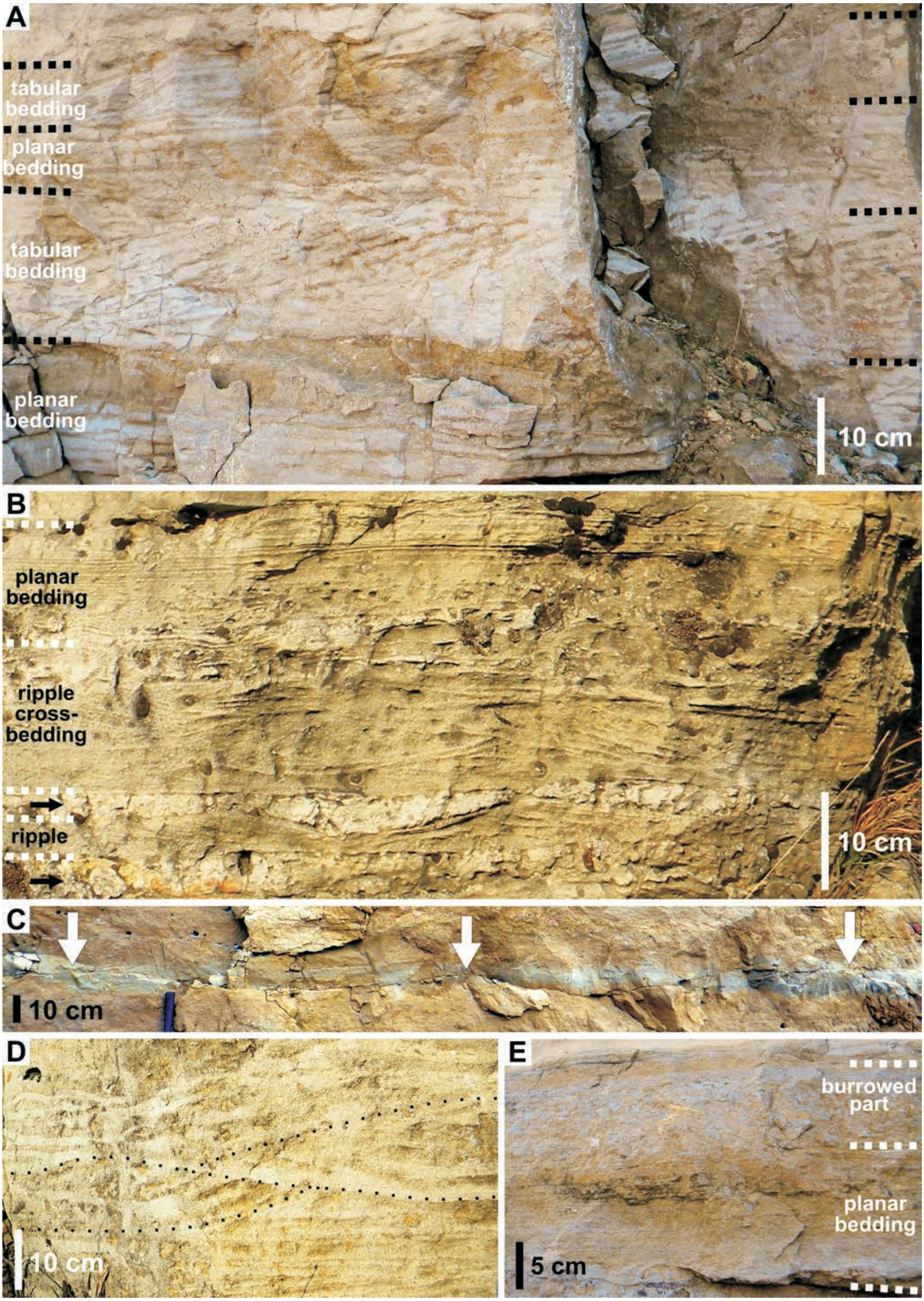
Description

Undolomitized deposits of Unit 2 were not exposed in any of the outcrops investigated. This unit is predominantly composed of beige-red-brown, medium- to coarse-grained pelolites, grainstones-packstones (Figs 2, 8A). In addition to, dominant peloids, disarticulated crinoids, and numerous bivalves and gastropods occur (Fig. 8B). The (pre-existing) shells are commonly oriented parallel to the bedding, convex-up and are mostly dissolved, giving rise to moldic porosity (Fig. 8C). In thin sections, the pelolites exhibit medium- to coarse-crystalline microtexture. However, occasionally the size, shape and arrangement of peloids are recognizable, where epigenetic dolomitization affected only the peloids and not the cements or interparticle pores (Fig. 8D). In such cases, the peloids are usually well rounded and moderately to well sorted. Observations of the silica nodules under the microscope revealed numerous ooids (Fig. 8E), which imply that at least part of the dolomitized peloids had well-developed ooidal cortices, prior to burial diagenesis. The pelolites comprise rare cavernous vugs (*sensu* Lucia, 1983), which reach 50 cm in size (Fig. 8F).

The pelolites (and oolites) form amalgamated packages, several metres thick. Each package shows complex sedimentary structures: planar bedding, low- and high-angle (tabular) cross-bedding, trough cross-bedding, herringbone cross-bedding, symmetrical and asymmetrical ripples with small-scale cross-bedding (20–40 cm long and 3–6 cm high), and rare dunes (0.4–5 m long and 10–20 cm high; Fig. 9A–D). The cross-laminae dip dominantly in two opposite directions: from N to W and from S to E; however, some bedsets are locally inclined to the NE or SW (Fig. 2). The ripple and dune crests are generally oriented NE–SW.

The pelolitic-oolitic packages are rarely intercalated with beige-red-brown intensively bioturbated dolosiltites and fine-grained dolarenites, which range in thickness from 10 to 50 cm (sporadically up to 1 m; Fig. 9E).

Unit 2 (and the Olkusz Beds) terminates with a regional disconformity, which marks the Sequence Boundary, defined by Szulc (2000). Near the Devonian islands, this boundary is very clearly visible as an erosional disconformity overlain by onlapping peritidal facies, whereas towards the central part of the Kraków-Silesia region, the contact is more conformable and hence the sequence boundary is less evident. The exposure of the underlying strata to a meteoric diagenetic environment resulted in the leaching of high-Mg calcite and aragonite, and the resultant development of non-touching moldic pores (*sensu* Lucia, 1983; Fig. 5D, E). Moldic porosity was also recognized in the oncoidal-peloidal limestones of the Gorażdże Formation (Szulc, 1999), which constitutes the stratigraphic equivalent in the Opole region (Fig. 3). The disconformity (sequence boundary) probably corresponds to the “erosional surface” recognized by Pawłowska and Szuwarzyński (1979) as occurring over the entire area of the currently closed “Trzebionka” lead-zinc mine, in the uppermost part of their unit 5.


A
tabular bedding
planar bedding
tabular bedding
planar bedding
10 cm
B
planar bedding
ripple cross-bedding
ripple
10 cm
C
10 cm
D
10 cm
E
burrowed part
planar bedding
5 cm

Lateral variability

Unit 2 is relatively uniform on a regional scale (Fig. 2), so the only minor local differences need to be emphasized. In the surroundings of the archipelago, Unit 2 is completely devoid of bioturbated fine-grained deposits, which in most sections constitute 10–50 cm thick intercalations of pelolites. In the vicinity of the "Olkusz-Pomorzany" Mine, in turn, these bioturbated deposits form unusually thick packages (1–2.5 m in thickness), but this may arise from mistakes made in describing the unslabbed drill cores.

Pelolites, occuring in close proximity to the Devonian islands (up to 200 m from the cliff walls) at Nowa Wioska, are usually finer-grained than in the other sections. The sediments, situated more than 200 m away from the cliff walls, are dominated by coarse-grained pelolites, often displaying large-scale high-angle cross-bedding and thick laterally-accreted bedsets (Fig. 10A, B). In addition, they comprise well-rounded, cross-laminated pelolitic intraclasts (pebbles to boulders), derived from the underlying lithified pelolites (Fig. 10C).

The thickness of Unit 2 is between 6 m (at Jaroszowiec) and 12 m (at Nowa Wioska; Fig. 2). These two sections were located close to two separate Devonian islands, indicating the strong influence of local subsidence and/or synsedimentary tectonics on sedimentary thicknesses.

Interpretation

The general scarcity of fine-grained sediments and the dominance of pelolites, displaying various large-scale sedimentary structures, indicate sedimentation above the normal wave-base. The calcareous sands were predominantly deposited by unidirectional strong currents in the upper shoreface setting, as indicated by common trough and tabular cross-bedding (e.g., Reading, 1978). After deposition, however, the sand must have been affected by waves, because many ripples and dunes have symmetrical shapes. Herringbone cross-bedding within some bedsets indicates deposition from reversing currents of equal intensity, which implies a tidal origin. The development of ooids also required a contribution of tidal currents (Rankey *et al.*, 2006; Reeder and Rankey, 2009; Rankey and Reeder, 2010, 2011). Planar bedding, typical of upper plane bed conditions, indicates temporary sedimentation in the foreshore (e.g., Reading, 1978). The convex-up orientation of shells confirms the high-energy regime; shells deposited from suspension are typically oriented convex-down (e.g., Clifton, 1971), but they invert to a more hydrodynamically stable convex-up position, when subjected to current or wave activity (e.g., Brenchley and Newall, 1970). Moreover, low diversity of benthos, represented chiefly by bivalves and gastropods, also should be attributed to substrate unstability, rather than to elevated salinity or oxygen deficiency, because the presence of crinoids indicates normal-marine conditions. In periods of greater substrate stability, the sandy bottom was intensively colonized by infauna. Lithification of the carbonate sands was locally rapid, since pebbles to boulders of cross-laminated pelolites were found to be incorporated into younger peloidal sands at Nowa Wioska. However, the overall lack of intraclasts excludes early marine cementation as a common phenomenon.

Unit 2 is interpreted to have been a limestone before the epigenetic dolomitization, because: 1) all lithological and sedimentary features of these deposits attest to a high-energy environment, eliminating the conditions of stagnation and elevated salinity that are responsible for the generation of evaporitive pore fluids and contemporaneous dolomitization of sediment (Warren, 2000); and 2) it is likely that any hypothetical meteoric waters or hypersaline seawater, infiltrating downward from the regional exposure surface or onlapping the peritidal areas, also would have penetrated further down through the limestones of Unit 1. This was not the case, because Unit 1 displays no epigenetic alteration.

Unit 3

Unit 3 overlies the regional disconformity mentioned above (Figs 10B, 11A, B), which is regarded as the sequence boundary (Szulc, 2000). The unit approximately corresponds to the "lower complex" of the Diplopora Beds *sensu* Myszkowska (1992; Figs 2, 3).

Description

The most characteristic lithofacies of Unit 3 are yellow cryptalgal laminites (planar stromatolites; Fig. 2). They are composed of alternating millimetre-thick laminae of microbial and detrital origins. The microbial laminae display dense aphanitic (minor clotted-micropeloidal) microfabric, whereas the detrital laminae are composed of silt- to mud-size lime particles (Fig. 11C, D). The lamination is more-or-less straight and parallel to the bedding planes. However, layers of laminae are often truncated and discordantly capped by other stromatolitic layers. In some cases, the lamination is barely seen, owing to a reduced contribution of microbial mats. Laminitic layers are commonly torn up into intraclasts, which may be incorporated into the successive laminations or form conglomerates and breccias (Fig. 11C). Flat and rounded intraclasts may be imbricated (Fig. 11E). The cryptalgal laminites occasionally contain fenestral pores, sheet cracks and mudcracks (Fig. 11F), but this facies is generally non-porous. Small gastropods can be found within the laminations.

◄

Fig. 9. Sedimentary structures of Unit 2. **A.** Vertical outcrop view of tabular cross-bedded pelolites alternated by planar-bedded ones. Pogorzyce – "Żelatowa" Quarry. **B.** Vertical outcrop view of small-scale cross-bedded pelolites, sandwiched between fair-weather fine-grained epigenetic dolostones (black arrows), capped by planar-bedded, coarse-grained pelolite. Imielin – abandoned quarry. **C.** Vertical outcrop view of symmetrical pelolitic dunes (white arrows). Nowa Wioska – "GZD" Quarry. **D.** Vertical outcrop view of trough cross-bedded, coarse-grained pelolite. Imielin – abandoned quarry. **E.** Vertical outcrop view of planar-bedded, coarse-grained pelolite. Distinct bioturbation in the upper part. Pogorzyce – "Żelatowa" Quarry.

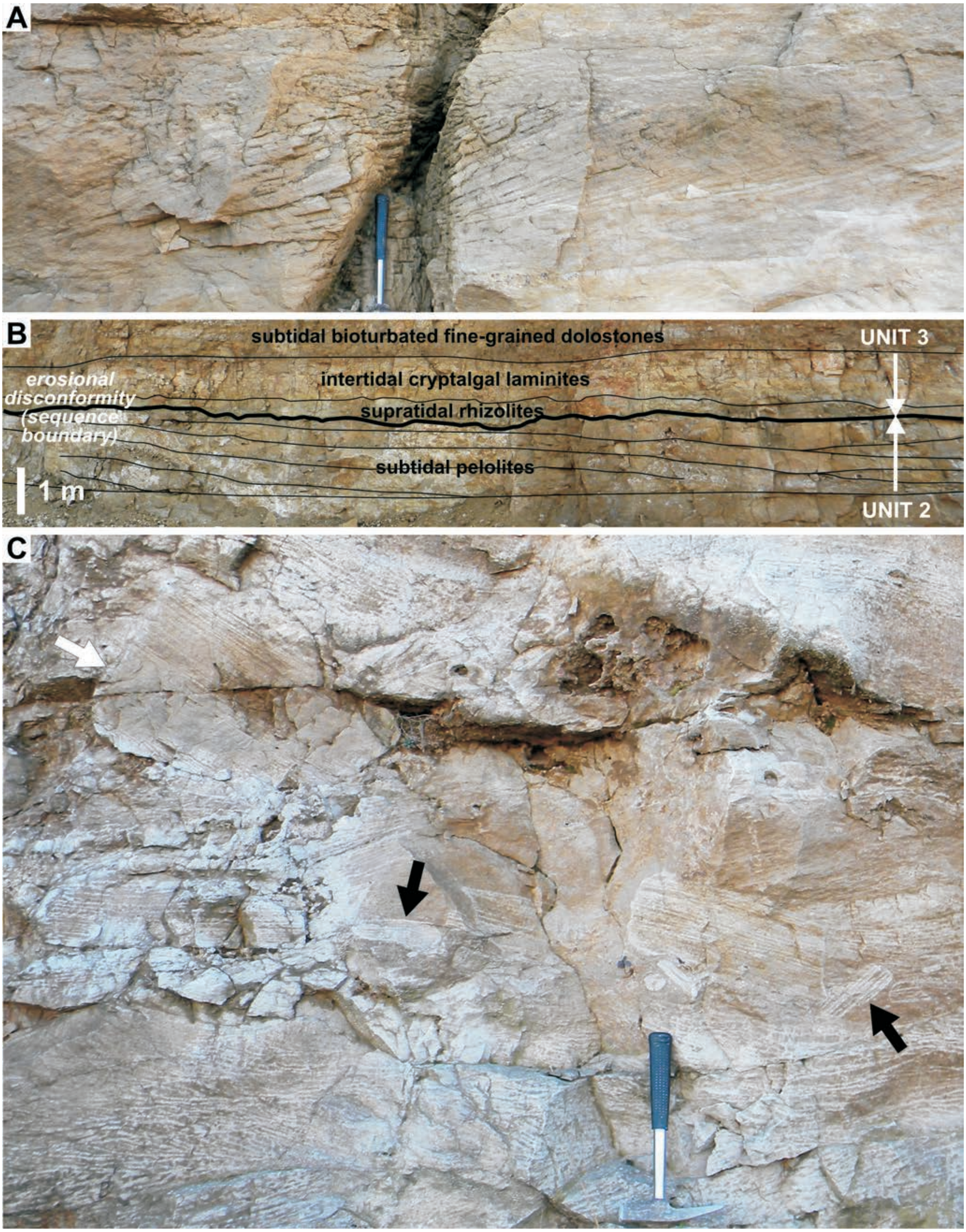


Fig. 10. Sedimentary structures of Unit 2. Nowa Wioska – "GZD" Quarry. **A.** Vertical outcrop view of high-angle cross-stratification with tangential relationship to the basal surface. Hammer for scale is 30 cm long. **B.** Vertical outcrop view of laterally accreting large-scale pelolitic bedsets, truncated during emersion and capped by peritidal facies. **C.** Vertical outcrop view of cross-stratified, coarse-grained pelolites containing numerous reworked pelolite intraclasts. White arrow points at 40 cm long cross-laminated intraclast of pelolite, black arrows point at smaller ones. Hammer for scale is 30 cm long.

Dolocretes, rhizolites and mudstones are also indicative of Unit 3 (Fig. 2). The dolocretes, yellow-orange-green-grey dolosiltites, create centimetre- to decimetre-thick crusts, resting usually on top of irregular subaerially weathered surfaces (Fig. 12A). Most dolocretes show nodular fabric, composed of microspar (Fig. 12B). Some dolocretes are structureless (massive) and contain peloids of dense aphanitic automicrite, embedded within allomicrite or microspar (Fig. 12C). The dolocretes are sporadically reworked to form breccias. The rhizolites, on the other hand, are beige-green massive dolosiltites with centimetre-long vertical, straight or bifurcating root casts (Fig. 12D). The amount of root casts usually increases upward within a rhi- zolite layer and consequently its topmost part contains a complex network of filiform voids. Root penetration never exceeds 15 cm depth. The rhizolites may contain single centimetre-sized lenses of sulphates (Fig. 12E, F). In turn, the mudstones are green and laminated. They form centimetre-thick layers, capping irregular, subaerially weathered surfaces. In thin sections, one can observe rounded quartz grains and muscovite platelets, scattered in carbonate mud (Fig. 12G, H).

The layers of cryptalgal laminites, dolocretes, rhizolites and mudstones are horizontally discontinuous on a local scale (within one outcrop) and all these lithofacies can pass laterally into each other. They form decimetre- to metre-thick packages, which pinch out laterally on a regional scale (tens of kilometres), but in places on a local scale, as well. The lateral persistence of lithofacies and the high-frequency cyclicity will be discussed in a separate paper.

The packages of cryptalgal laminites, dolocretes, rhizolites and mudstones are intercalated with decimetre- to metre-thick packages of bioturbated dolosiltites and/or pelolites (Fig. 3). The bioturbated dolosiltites are yellow-orange-grey cavernous, unfossiliferous rocks with irregular spots, although some bedsets include *Thalassinoides* isp., instead of irregular spots (Fig. 13A, B). Under the microscope, one can sometimes recognize micrite and microspar, but usually the microfabric is epigenetically dolomitized. On the other hand, the pelolites are yellow-orange-grey dolosiltites and fine- to medium-grained dolarenites, grainstones-packstones, which usually display medium- to coarse-crystalline microtexture (Fig. 13C). Locally, flat and well-rounded lithoclasts of cryptalgal laminites are embedded, especially at the contacts with the underlying laminites. Green algae are most common amongst the scarce skeletal fossils (Fig. 13D). The pelolites show various, albeit rare, sedimentary structures: planar bedding, low- and high-angle cross-bedding, trough cross-bedding as well as dunes 0.5–1.5 m long and 5–10 cm high (Figs 2, 13E). Sedimentary structures are in places disturbed by burrows *Thalassinoides*.

Lateral variability

As described above, Unit 3 is made up of packages of cryptalgal laminites, dolocretes, rhizolites and mudstones, alternating with packages of pelolites and bioturbated dolosiltites. The thickness of the former packages usually does not exceed 1 m in most sections. It reaches only 20 cm in Libiąż and Jaroszowiec, and 1–3 m at Nowa Wioska (Fig. 2). Furthemore, at Nowa Wioska, these packages are occasionally cut by tidal channels, reaching 20 m in width and 3 m in depth. The pelolites, filling the channels, accreted transversely with respect to the main direction of tidal-channel propagation and sometimes contain angular lithoclasts of dolosiltites, dolocretes and Devonian dolostones (Fig. 13G).

The pelolites at Libiąż comprise abundant flat and rounded lithoclasts, aligned more-or-less parallel to the bedding planes (Fig. 13F). The lithoclasts are composed of microspar, and contain rare forams. This kind of deposit has not been found *in situ* at Libiąż, so the lithoclasts must have been transported from outside.

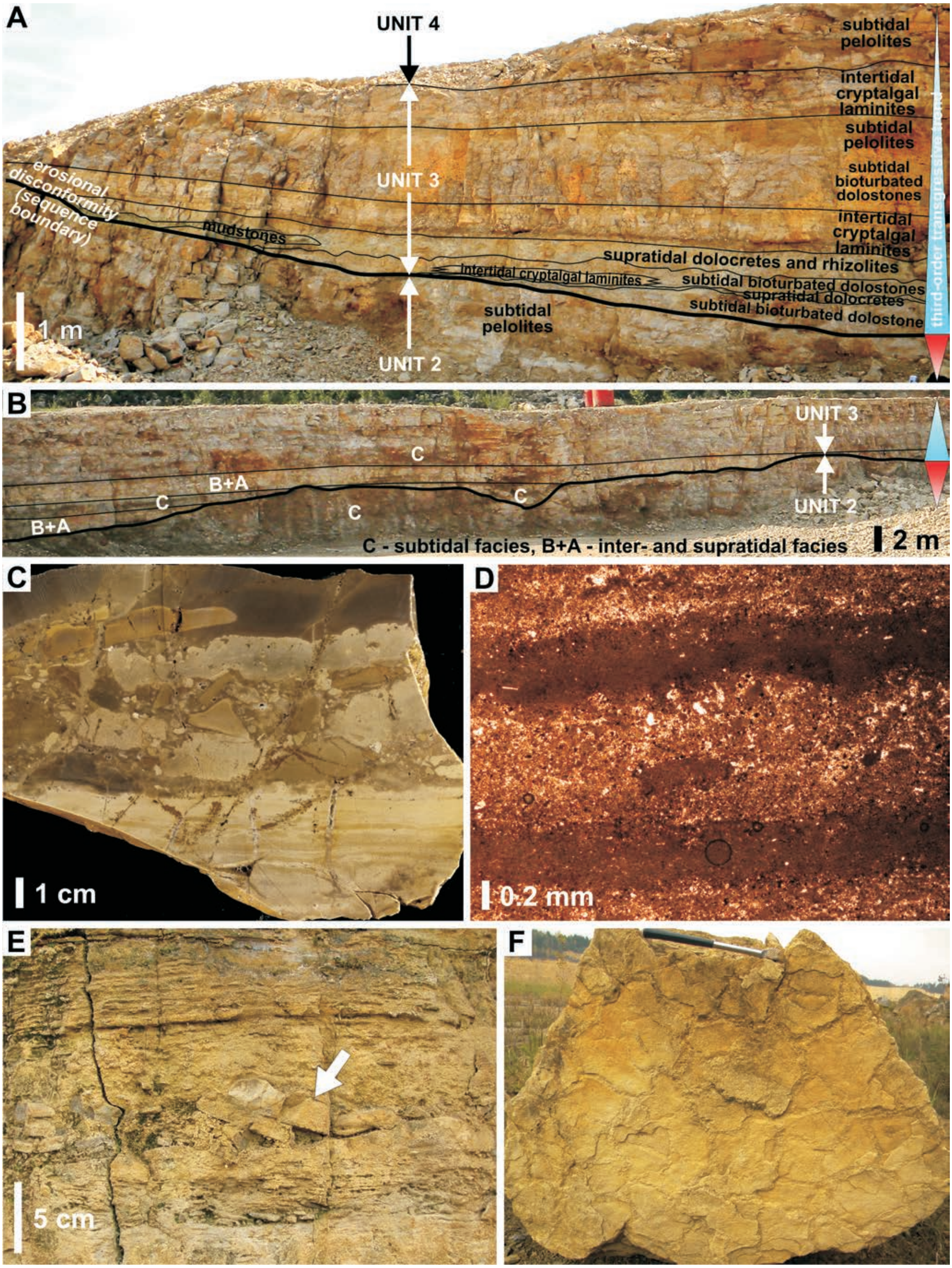
The thickness of Unit 3, reaching 10–14 m in most sections, is reduced to 5–7 m at Dąbrowa Górnicza, Bukowno and Jaroszowiec (Fig. 2). These three sections were situated close to two Devonian islands and experienced a similar evolution, controlled by local subsidence. Unit 3 pinches out to the west and is totally absent at Tarnowskie Góry.

Interpretation

The dolocretes and mudstones are interpreted as having formed in the supratidal zone, on emerged banks and peripheral plains of tidal flats. Dolocretes are a widely accepted indicator of semi-arid and arid conditions (Esteban and Klappa, 1983). However, the scarcity of evaporites seems to exclude intense evaporation in this case. The rhizolites also could have been formed in permanently emerged areas, but they may represent intertidal salt marshes, as well (Shinn *et al.*, 1969). Only small plants grew in these areas, as indicated by the small size of the root casts. This may be due to a relatively arid climate and/or substrate instability (e.g., due to the activity of tidal currents).

The cryptalgal laminites formed in the intertidal zone of tidal flats, as a consequence of the trapping of carbonate mud by microbial mats (Ginsburg, 1960; Fischer, 1964; Kendall and Skipwith, 1968; Shinn *et al.*, 1969; Hardie, 1977; Kinsman and Park, 1976; Shinn, 1983; Alsharhan and Kendall, 2003; Rankey and Berkeley, 2012). The mud was apparently deposited from suspension in a relatively calm environment, as evidenced by the straight laminations. Lack of bioclasts and coarse sediment may reflect a larger distance to the subtidal zones and/or limited storm-generated transport (e.g., Pratt and James, 1986). However, the area was not completely separated from high-energy processes. Tidal currents were most likely responsible for truncation of the laminite layers and for producing intraclasts. Locally, intense reworking resulted in decimetre-thick breccias and conglomerates (e.g., at Nowa Wioska). The non-porous fabric of the cryptalgal laminites indicates that the deposit was regularly flooded, without prolonged desiccation; otherwise this facies would comprise abundant mudcracks, sheet cracks or fenestral pores (e.g., Fischer, 1964; Shinn, 1968), which is not the case. The gastropods, found within laminites, are interpreted as *in situ* accumulations of mat-grazing organisms.

The bioturbated dolostones are interpreted as shallow subtidal sediments, deposited in areas protected from vigorous tidal currents. The thinner units of bioturbated dolostones might have been formed in ephemeral tidal ponds (e.g., Shinn *et al.*, 1969; Rankey and Berkeley, 2012), whereas


A
UNIT 4
subtidal pelolites
intertidal cryptalgal laminites
subtidal pelolites
subtidal bioturbated dolostones
intertidal cryptalgal laminites
UNIT 3
erosional disconformity (sequence boundary)
mudstones
supratidal dolocretes and rhizolites
intertidal cryptalgal laminites
subtidal bioturbated dolostones
supratidal dolocretes
subtidal bioturbated dolostone
subtidal pelolites
UNIT 2
1 m
third-order transgressive trend
B
UNIT 3
UNIT 2
C
B+A
C
B+A
C
C
C - subtidal facies, B+A - inter- and supratidal facies
2 m
C
1 cm
D
0.2 mm
E
5 cm
F

the thicker ones were more likely to have been deposited in lagoons and embayments (e.g., Kendall and Skipwith, 1969; Purser and Evans, 1973; Alsharhan and Kendall, 2003). The absence of skeletal fossils indicates restricted life conditions with probably elevated salinity, however, allowing pervasive bioturbation. *Thalassinoides* isp. indicates good oxygenation of the deposit (e.g., Rhoads, 1975; Savrda and Bottjer, 1986; Savrda, 2007).

The pelolites are interpreted as representing the shallow subtidal zone, as well. Some of the peloids were transported into high-energy conditions (bars or shoals), as indicated by occasional current cross-bedding. However, most of the peloids were accumulated in relatively tranquil, albeit generally mud-free areas. The overall paucity of skeletal fossils again seems to reflect elevated salinity.

The cyclic alternation of supra-intertidal facies and shallow subtidal facies proves that Unit 3 represents a tidal flat system, which periodically experienced longer periods of submersion. The frequency of these changes varied between the sites (depending on the relative distance to the open sea in the west and differring subsidence rates), indicated by regionally variable thicknesses of the lithofacies packages (Fig. 2). The surroundings of Nowa Wioska apparently were occupied by tidal flats for a relatively long time, because here the packages of supra-intertidal facies commonly reach 1–3 m in thickness. In contrast, the other areas underwent geomorphic changes more frequently, recorded as thinner and more frequent intercalations of different peritidal facies. All tidal flats showed a distinct morphological differentiation and encompassed co-existing cyanobacterial mat flats, salt marshes and emerged areas, as evidenced by supra- and intertidal lithofacies passing laterally into one another. Locally, the tidal flats were cut by tidal channels. Carbonate mud was deposited in protected, shallow subtidal areas (ephemeral tidal ponds, and lagoons or embayments of longer existence), whereas peloidal sands characterized high-energy settings (bars or banks).

By analogy to many Phanerozoic successions (e.g., Fischer, 1964; Pratt and James, 1986; Adams and Grotzinger, 1996; Bádenas *et al.*, 2010) and modern sedimentary analogues (e.g., Illing *et al.*, 1965; McKenzie, 1981; Shinn, 1983), the supra- and intertidal facies of Unit 3 are interpreted as early diagenetic dolostone, which subsequently underwent epigenetic dolomitization. The subtidal facies might have been a limestone; however, it is more likely that they were dolomitized in their early diagenetic history by continental groundwater or hypersaline seawater, percolating downward from prograding supra- and intertidal areas (Warren, 2000).

Unit 4

Unit 4 approximately corresponds to the “middle complex” of the Diplopora Beds *sensu* Myszkowska (1992; Figs 2, 3).

Description

In many sections, the upper limit of epigenetic dolomitization occurs within Unit 4 and therefore its lower part is characterized by orange colours and crystalline microtexture, whereas the upper part has yellow colours and preserved the original microtexture much better (although altered by early diagenesis). Notwithstanding these differences, Unit 4 is predominantly composed of medium- to thickly-bedded (10–100 cm) pelolites, grainstones-packstones (Fig. 2). These are fine- to coarse-grained dolarenites and sporadically dolosiltites, some of which contain disarticulated crinoids, bivalves, gastropods and green algae (Fig. 14A–C). Peloids are mostly well rounded and moderately sorted. The pelolite beds hardly ever display internal cross-bedding (trough cross-bedding, herringbone cross-bedding, planar bedding). However, the tops may be shaped in the form of symmetrical ripples (10–20 cm long and 3–5 cm high) or dunes (0.4–1.5 m long and 5–10 cm high; Fig. 14D, E). The crestlines of ripples and dunes run generally NE–SW (Fig. 2). Locally, the pelolites comprise a well-developed network of burrows *Balanoglossites* or *Thalassinoides*, which may completely alter the sedimentary fabrics (Fig. 14F, G). Decimetre- to metre-thick packages of pelolites are intercalated with bioturbated dolosiltites, which often contain cavernous vugs and the ichnofacies mentioned above.

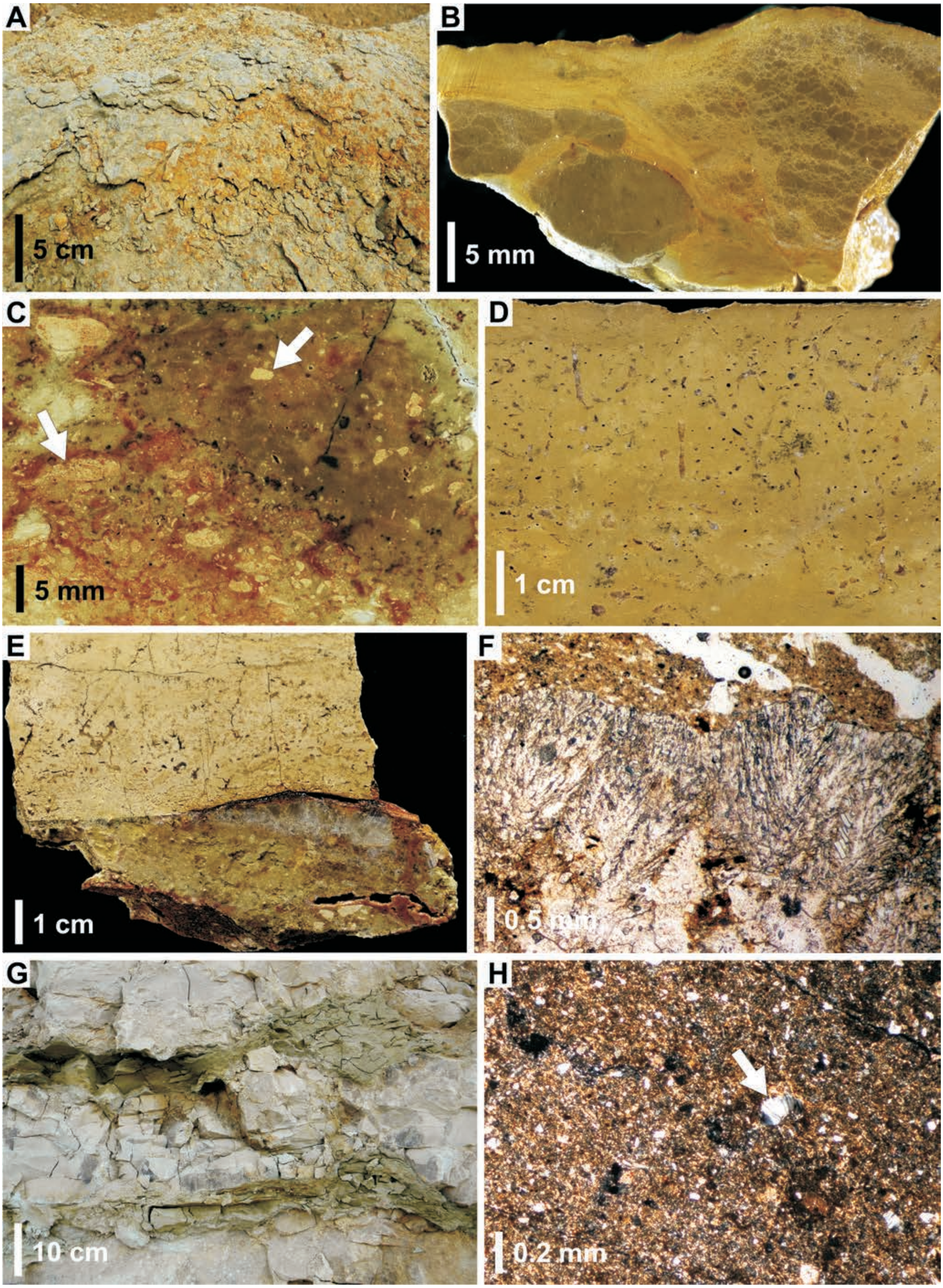
Lateral variability

Unit 4 is relatively uniform on a regional scale. It has a thickness of 9–12 m, except at Pogorzyce, where it reaches 15 m (Fig. 2). The bioturbated dolosiltites, constituting subordinate intercalations of thick pelolitic packages in most sections, form units 1.5–2.5 m thick at Dąbrowa Górnicza and Bukowno.

Upper boundary

Unit 4 is overlain by an oncolitic package 5–10 m thick and regarded as a correlation horizon across the entire Kraków-Silesia region (Alexandrowicz, 1971; Bilan and Golonka, 1972). At Nowa Wioska and Libiąż, however, *Diplopora* (green algal) grainstones occur instead of oncolites (Fig. 2).

Fig. 11. Main lithological features of Unit 3. **A.** General view of subaerially exposed upper shoreface-foreshore facies of Unit 2, onlapped by peritidal facies of Unit 3. The disappearance of the inter- and supratidal facies in the succession marks the lower boundary of Unit 4. Nowa Wioska – “GZD” Quarry. **B.** General view of the peritidal facies capping the subtle platform topography. Nowa Wioska – “GZD” Quarry. **C–F.** Intertidal facies of Unit 3. **C.** Vertically oriented slab of reworked cryptalgal laminite (upper part) capping laminite in place. Nowa Wioska – “GZD” Quarry. **D.** Photomicrograph of cryptalgal laminite: darker microbial laminae alternate with more transparent detrital ones. Bolęcin – “Skała Bolęcka” Quarry. **E.** Vertical outcrop view of imbricated intraclasts (white arrow) within cryptalgal laminite. “Libiąż” Quarry. **F.** Bedding plane view of mudcracks developed within cryptalgal laminite. Hammer for scale is 30 cm long. Pogorzyce – “Żelatowa” Quarry.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Interpretation

The overall predominance of pelolites over fine-grained sediments indicates that sedimentation took place in a shallow-marine environment, in which the energy was high enough to winnow calcareous mud to more quiescent zones of the basin and produce grain-supported textures. Because current cross-bedding is uncommon in these deposits, wave action is considered to have been the principal factor involved in removing the mud. Relatively abundant symmetrical ripples and dunes corroborate this interpretation. It is likely, therefore, that the area was protected from the influence of strong currents, but was subjected to wave activity. Common green algae confirm the transparency of the water column and at least periodic stability of the substrate. The crinoids indicate normal marine conditions.

Although peloidal sedimentation dominated in the Kraków-Silesia region, mud sedimentation was locally of great importance (at Bukowno and Dąbrowa Górnicza). The completely bioturbated nature of these muds and the occurence of *Thalassinoides* isp. indicates good oxygenation of the deposits (e.g., Rhoads, 1975; Savrda and Bottjer, 1986; Savrda, 2007).

The upper part of Unit 4, not affected by the epigenetic dolomitization, is characterized by a relatively stable MgO content (19–21%), as compared to the typical "ore-bearing dolomites" (Śliwiński, 1966b). A similar stability of MgO content is also characteristic of the Röt dolostones and the Middle Muschelkalk dolostones, widely regarded as early diagenetic dolomites (e.g., Śliwiński, 1966b). Unit 4 is therefore interpreted to have been a limestone which firstly underwent the early diagenetic dolomitization, and then its lower part was replaced by the epigenetic dolomite. The most probable mechanism of the early dolomitization was the reflux of Mg-rich brines from the shallower parts of the platform (Warren, 2000).

LONG-TERM EVOLUTION OF THE KRAKÓW-SILESIA SUB-BASIN

The long-term facies succession of the Kraków-Silesia Sub-basin reflects third-order transgressive-regressive pulses, which strongly controlled both depth (energy regime) and siliciclastic input (Szulc, 2000). The topmost part of the Gogolin Formation, composed mainly of the wavy-nodular, clay-rich *Rhizocorallium*-bearing calcilutites, represents sedimentation in fully marine conditions, under a significant influx of terrigenous material and at depths below the storm wave-base (offshore). Sporadic intercalations of bioclastic wackestones-packstones and hummocky cross-stratified calcisiltites resulted from severe storms, rather than high-frequency sea-level fluctuations (Matysik, 2012).

The disappearance of these strata indicates major changes in sedimentation style within the Kraków-Silesia Sub-basin. First of all, the Sub-basin became isolated from terrigenous influx, as shown by the total absence of siliciclastics within Unit 1. This implies that the broad areas of the neighbouring Małopolska Massif became flooded. The cessation of terrigenous input was not synchronous, but migrated diachronously from the SW to NE: the wavy-nodular, clay-rich limestones disappear first in the western- and southernmost sections (Tarnowskie Góry and Imielin, respectively), and only later in the eastern sections (Dąbrowa Górnicza, Bukowno; Fig. 2). Secondly, the general sedimentation character changed from relatively constant to highly episodic, since the uniform wavy-nodular *Rhizocorallium*-bearing limestones were replaced by *Balanoglossites and Thalassinoides* firmgrounds. In addition, the bioclast-dominated tempestites were totally replaced by peloid-dominated ones, containing only subordinate amount of skeletal fossils. This change suggests massive redistribution of peloids from the adjacent shallow-water sources, which might have been caused by a significant expansion of "carbonate factories", probably due to the widespread flooding of land areas. On the basis of these considerations, the boundary between the Gogolin Formation and Olkusz Beds is regarded herein as the Maximum Flooding Surface (MFS).

The Olkusz Beds, overlying the MFS, displays a shoaling-upward trend, the transition from lower shoreface facies (Unit 1) *via* upper shoreface-foreshore facies (Unit 2) to the final emersion. Such a regressive trend is typical of highstand system tracts (e.g., Catuneanu *et al.*, 2010). Unit 1 itself also shows a shallowing-upward tendency, expressed by the increasing thickness and abundance of pelolitic intercalations within the firmground succession. Some areas, such as the Imielin site, already rose above the normal wave base during this time, evidenced by 2 m thick pelolitic packages that exhibit various high-energy sedimentary structures including herringbone cross-bedding. As a result of the progressive filling of the sub-basin (and possible a third-order eustatic sea-level drop), the whole Kraków-Silesia region finally rose up to and above the normal wave base and consequently sedimentation of high-energy peloidal-ooidal sands (Unit 2) commenced. The major unknown is how many peloids had been ooids, prior to the epigenetic dolomitization. On the basis of microscopic observations of the silica nodules, some pelolites clearly contain abundant ooids and should be classified therefore as oolites (Fig. 8E). In addition, the pelolites that display only partially obliterated microtexture are composed of well rounded, well

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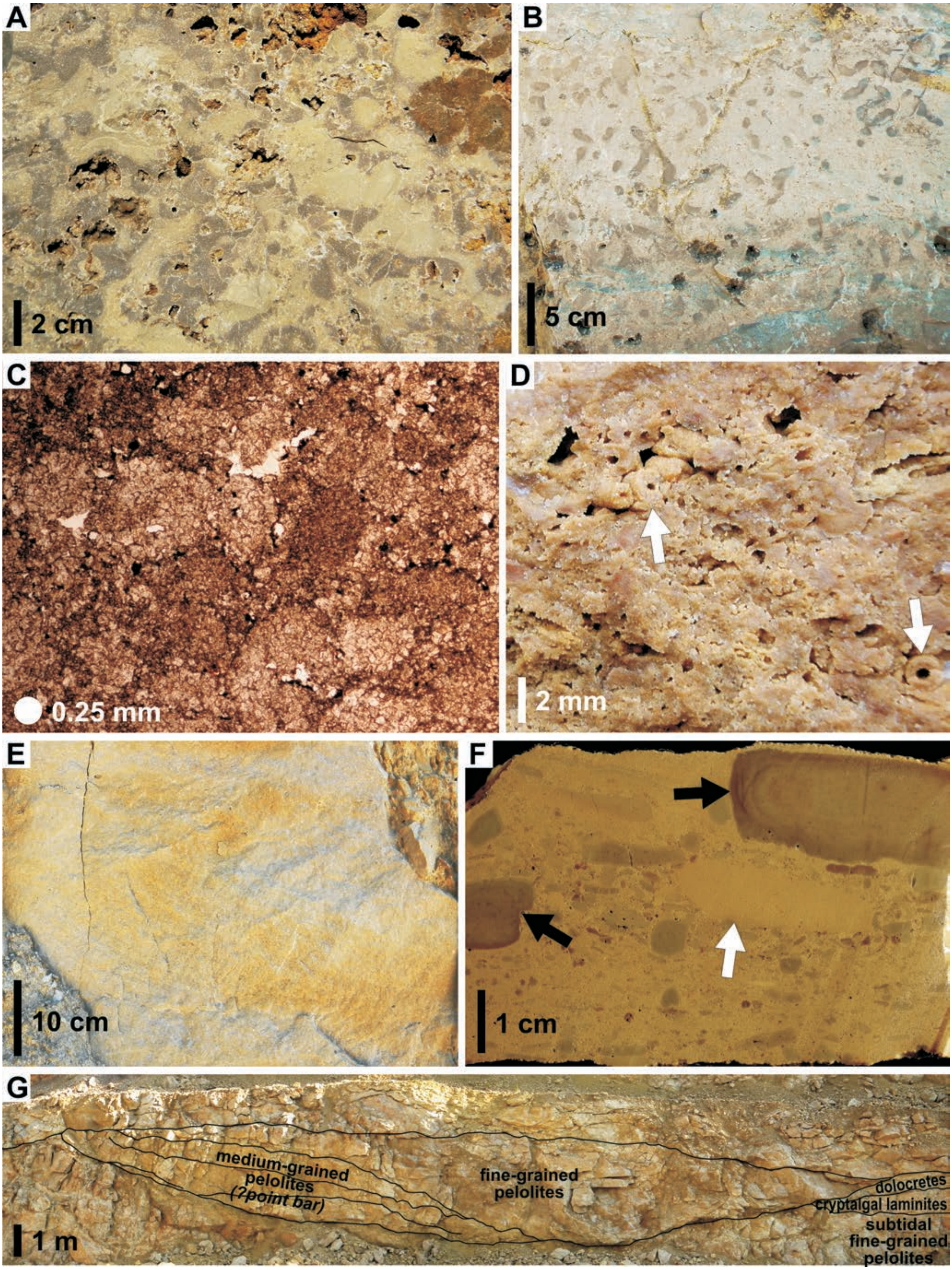
Fig. 12. Supratidal facies of Unit 3. **A.** Bedding plane view of dolocrete crust. Dąbrowa Górnicza – "Ząbkowice" Quarry. **B.** Vertically oriented slab of nodular dolocrete. "Libiąż" Quarry. **C.** Vertically oriented slab of structureless dolocrete, containing automicritic peloids and lithoclasts (white arrows). "Libiąż" Quarry. **D.** Vertically oriented slab of a rhizolite with small vertical root casts. "Libiąż" Quarry. **E.** Vertically oriented slab of nodular evaporite occuring within a rhizolite layer. Nowa Wioska – "GZD" Quarry. **F.** Photomicrograph of E, showing sulphate crystals. **G.** Vertical outcrop view of two greenish mudstone layers, separating whitish fine-grained pelolites. Nowa Wioska – "GZD" Quarry. **H.** Photomicrograph of G, illustrating quartz grains (white arrow) scattered in carbonate matrix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cryptalgal laminites
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sorted peloids (Fig. 8D), which resemble the Recent ooids forming in the tidal deltas and banks of the Bahamas (Rankey *et al.*, 2006; Reeder and Rankey, 2009; Rankey and Reeder, 2010, 2011). It is possible that most of the pelolites discussed were originally oolites. If this were to be the case, the waters of the Kraków-Silesian Sub-basin must have been oversaturated with respect to carbonate and strongly agitated (e.g., due to the daily activity of tidal currents) to produce ooids (Rankey and Reeder, 2009; Duguid *et al.*, 2010). Such an interpretation is further corroborated by the presence of herringbone cross-bedding, indicative of tidally influenced settings.

Sedimentation of the Olkusz Beds was terminated by the emersion event. Its imprint on the underlying strata cannot be restored in detail because of the pervasive epigenetic dolomitization. Nevertheless, exposure to a meteoric-diagenetic environment certainly led to the leaching of aragonitic or high-Mg calcitic grains (peloids, ooids and bioclasts except for crinoids), as evidenced by the ubiquitous moldic porosity (Fig. 5D). It is noreworthy that the moldic pores (clearly visible both macro- and microscopically) are preserved only in the undolomitized deposits of the Olkusz Beds. This proves that the dolomitization process was responsible for the infilling of the pores by cement. The pores generally disappear near the lower boundary of the Olkusz Beds, indicating exposure of the entire formation and a sea-level drop of about 20–25 m. However, the possibility of a larger-scale regression cannot be excluded, and the lack of the diagnostic moldic pores within the underlying Gogolin Formation may have arisen from its different lithology (wavy-nodular clay-rich calcilutites and occasional bioclastic tempestites), which was much less susceptible to meteoric dissolution. The emersion event discussed was apparently too short to produce an extreme karstic topography or even small-scale karst features. In addition, limited annual precipitation typical of subtropical latitudes did not favour intense karstification (James and Choquette, 1988; Wright and Smart, 1994). Only at Nowa Wioska, peritidal facies transgressed onto a system of low-relief (1–3 m high and up to hundreds of metres across) morphologic depressions and elevations (Fig. 11A, B). No lag deposits, containing fragments of reworked basement, have been found, which argues against the complete erosion of the hypothetical, pre-existing karstified sediments.

The regional disconformity, marking the sequence boundary, is capped by peritidal facies (Unit 3 of the Diplopora Beds), which represent a tidal flat–lagoonal system established during the initial phase of transgression (Figs 10B, 11A, B). This system included a belt of channelized supratidal plains and banks, cyano-bacterial mat flats, salt marshes and possibly tidal ponds, which was flanked seawards (westwards) by a belt of low-energy mud-dominated lagoons and embayments, separated from each other and sheltered from the open sea by high-energy peloidal bars and shoals. As a result of high-frequency changes in accommodation space (whatever its origin), both belts migrated laterally and consequently encroached upon one another. This produced metre-scale cyclicity, clearly observable in vertical profiles (Figs 2, 11A). Despite the similarities, each locality displayed some sedimentological differences, for example, contrasts in thicknesses of the supra-intertidal and subtidal packages (Fig. 2), or the occurrence of additional lithofacies or grain types (Fig. 13F). The overall lack of evaporites in the system may reflect relatively humid climates, resulting from a monsoonal influence (e.g., Parrish and Peterson, 1988; Kutzbach and Gallimore, 1989; Van der Zwaan and Spaak, 1992; Parrish, 1993), or the proximity of the Tethys Ocean. Nevertheless, the common development of dolocrete crusts implies at least temporary semiarid conditions (Esteban and Klappa, 1983).

As a consequence of the progressive transgression, the tidal flat system became ultimately submerged and the Subbasin entered into a shallow subtidal zone, dominated by the accumulation of peloidal sands (Unit 4). The high-energy regime of this time controlled the overall paucity of carbonate mud. Apparently, the mud was removed to the basinal areas by wave action, as indicated by the general absence of current cross-bedding. The transparent waters and periodically stable substrate enhanced massive growth of fragile green algae requiring light.

The period of maximum flooding in the third-order transgressive-regressive pulse discussed seems to be expressed in the deposition of oncoidal and green algal sands, widely distributed across the Kraków-Silesia Sub-basin (Bilan and Golonka, 1972; Alexandrowicz, 1971; Myszkowska, 1992; this study). These strata are capped by about 25 m of peritidal facies (Fig. 3), which correspond to the "upper complex" of Myszkowska (1992).

Important information regarding the palaeogeography and evolution of the Kraków-Silesian Sub-basin was obtained from the analysis of the sedimentary structures. Inspection of the circular histograms revealed that for most sections the azimuth pattern is bipolar, with both modes more-or-less equally represented, which indicates a tidal and/or wave origin (Fig. 15). Furthermore, in the sections located outside the archipelago of the Devonian islands, the

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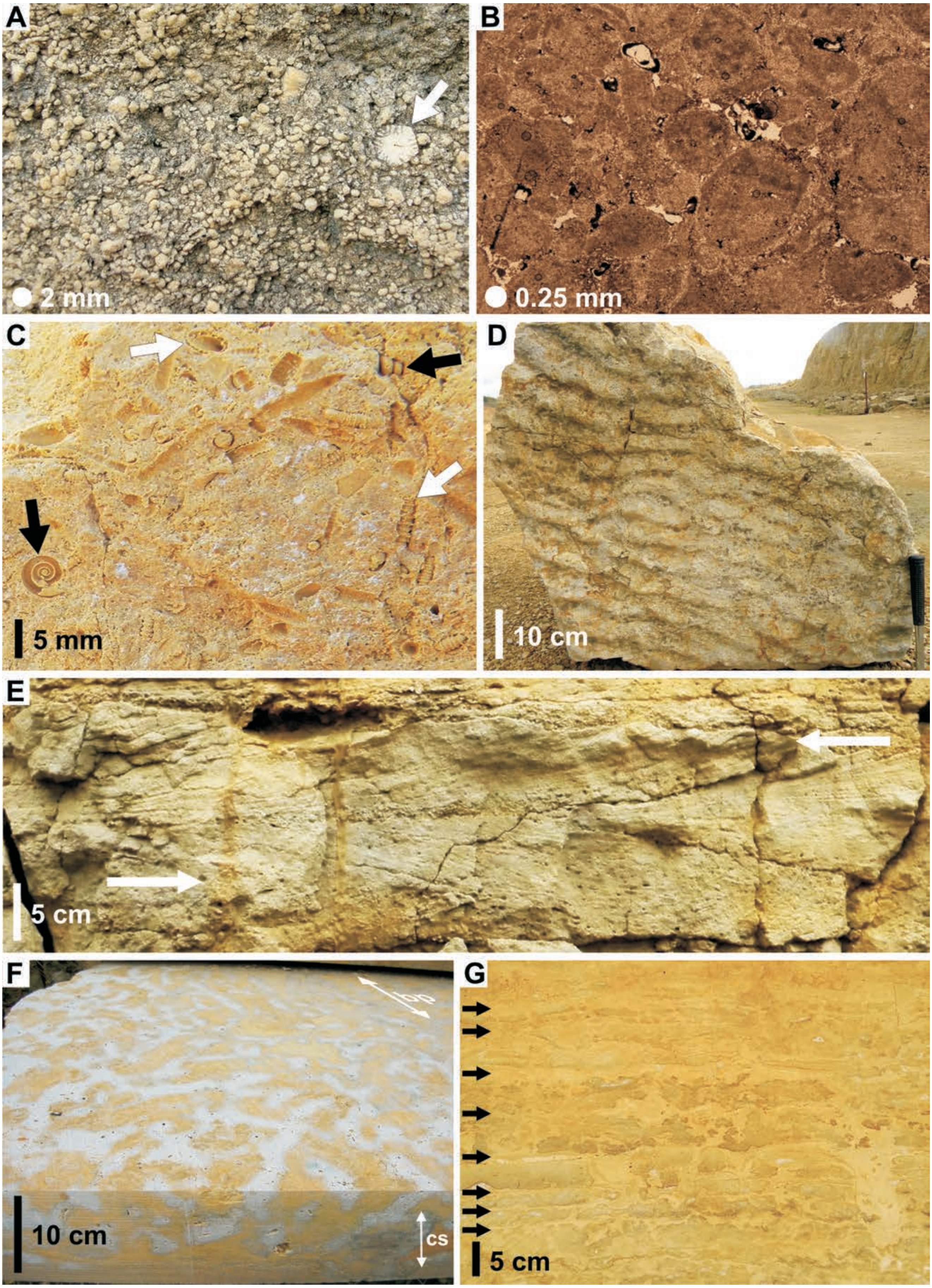
Fig. 13. Subtidal facies of Unit 3. **A.** Vertical outcrop view of spotted cavernous dolostone. Note that cavernous vugs are chiefly developed within dark grey irregular spots. Nowa Wioska – "GZD" Quarry. **B.** Vertical outcrop view of *Thalassinoides*-bearing dolosiltite. Nowa Wioska – "GZD" Quarry. **C.** Photomicrograph of pelolite, showing dolomitized microtexture of peloidal packstone. Despite crystal growth, particular peloids are still visible. Pogorzyce – "Żelatowa" Quarry. **D.** Vertical outcrop view of algal debris. White arrows point at well preserved tubes of green algae. "Libiąż" Quarry. **E.** Vertical outcrop view of trough cross-bedded, coarse-grained pelolite. Nowa Wioska – "GZD" Quarry. **F.** Vertically oriented slab of fine-grained pelolite, containing flat and rounded microsparite intraclasts (black arrows) and pelolitic intraclasts (white arrow). "Libiąż" Quarry. **G.** Vertical outcrop view of tidal channel, filled by peloidal sands and cutting various peritidal facies. Nowa Wioska – "TRIBAG" Quarry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sediment was clearly transported in a NW–SE direction, which seems to reflect the regional palaeocurrent pattern, controlled by the orientation of the palaeoshoreline. In the sections situated within the archipelago, in turn, the local directions of sediment transport diverge from the anticipated general one and tend to follow the geometry and orientation of the adjacent Devonian islands. It is also noteworthy that the majority of ripples and dunes over the entire area display different types of cross-bedding, resulting from unidirectional current flow, but they have a symmetrical shape, created by the oscillatory motion of bottom waters. This suggests that the sedimentary structures, formed in the initial stage as a response to current flow, were commonly remodelled in the final stage by waves.

REMARKS ON THE EPIGENETIC DOLOMITIZATION PROCESS IN THE KRAKÓW-SILESIA ORE PROVINCE

From comparisons of the undolomitized and "early dolomitic" lithologies with their epigenetically dolomitized counterparts (especially in Unit 1), it may be concluded that the migrating dolomitizing fluids caused three main changes in the original rock fabric: colour change, replacement by growing dolomite crystals, and the creation of porosity. On a regional scale, the degree of alteration depended on the distance to the main zones of fluid flow, the fault zones (Bogacz *et al.*, 1970; Gałkiewicz, 1971; Kibitlewski and Górecka, 1988; Górecka, 1993; Kibitlewski, 1993). On a local scale, it depended on the depositional facies of particular lithologies, which in turn strongly controlled their porosity and permeability. In other words, in the same area, the process of epigenetic dolomitization modified different lithologies in different ways. With respect to the intensity and type of change, the lithologies described may be grouped into three general categories: 1) cryptalgal laminites and emersion-related deposits; 2) coarse-grained deposits (mostly pelolites); and 3) bioturbated fine-grained deposits (mostly firmgrounds).

The cryptalgal laminites and emersion-related deposits

The cryptalgal laminites and emersion-related deposits, characteristic of Unit 3 and interpreted as early diagenetic dolomites prior to burial diagenesis, were affected by the epigenetic changes only locally and to a minor extent. In most sections, the original light colours (yellow, beige, orange, grey and green) are preserved, the fine texture is not dolomitized at all, and only sporadic and scattered small vugs are present. In sections situated close to the major faults (e.g., at Libiąż), the cryptalgal laminites have orangeish colours and indistinct biolamination; however, they are still less altered than the other deposits at the same location. The overall lack of alteration indicates that the stratigraphic horizons, composed of the cryptalgal laminites and emersion-related deposits, were not used as major routes of bed-parallel migration by the fluids causing burial dolomitization.

The coarse-grained deposits

The coarse-grained deposits are epigenetically dolomitized in most sections. The original white-grey pelolitic limestones with ubiquitous moldic porosity and frequent skeletal fossils (Unit 1 and Unit 2), and yellow-orange-grey pelolitic ?early diagenetic dolostones with scarce fossils (Unit 3 and Unit 4) were altered into beige-orange-red-brown epigenetic dolomites, displaying medium- to coarse-crystalline microtexture and containing steinkerns of mollusks as well as occasional cavernous vugs, up to 50 cm across.

Among the several types of change, dolomitization is the most obvious. In the majority of cases, it is not manifested macroscopically and accordingly sedimentary structures or individual grains can be easily distinguished. Instead, the process is visible under the microscope as a homogenous mass of dolomite crystals (Fig. 5C). In rare cases, where dolomitization was not very advanced, the dolomite crystals replaced exclusively peloids, without affecting the cements and interparticle pores (Fig. 8D). This clearly shows that the development of a crystalline microtexture started inside the grains, whereas the cements or interparticle pores were involved only at the end. According to Heijlen *et al.* (2003), the dolomitization process occurred in two separate stages: 1) the precipitation of iron-poor dolomite crystals (dolomite generation I); and 2) the crystallization of iron-rich dolomite rims (dolomite generation II) around the dolomite crystals of generation I. The presence of iron-rich dolomite rims also explains the typical colours of the ore-bearing dolomite.

Although dolomite cements fill many moldic pores, many of the biomolds remained open (Fig. 8B, C) and some of them were even enlarged during the dolomitization process to form larger vugs (Fig. 16A). The origin of the large (50 cm across) cavernous vugs is problematic. They occur sporadically and without any particular pattern of distribution (Fig. 8F).

Fig. 14. Main lithological features of Unit 4. **A.** Bedding plane view of coarse-grained peloidal packstone with sparse crinoid ossicles (white arrow). Pogorzyce – "Żelatowa" Quarry. **B.** Photomicrograph of A, showing well rounded and poorly sorted peloids. Note the beginning dolomitization of the texture. **C.** Bedding plane view of fine-grained peloidal packstone, containing frequent green algae (white arrows) and rare gastropods (black arrows). Nowa Wioska – "GZD" Quarry. **D.** Bedding plane view of symmetrical ripples. Dąbrowa Górnicza – "Ząbkowice" Quarry. **E.** Vertical outcrop view of medium-grained peloidal packstone, displaying herringbone cross-bedding. White arrows indicate direction of sediment transport. Pogorzyce – "Żelatowa" Quarry. **F.** Polished slab along bedding plane (bp) and cross-section (cs), illustrating dense network of the trace fossil *Balanoglossites* in three-dimensional view. "Libiąż" Quarry. **G.** Vertically oriented slab of planar-bedded fine-grained peloidal packstone containing *Balanoglossites*. Note that burrows form several well-developed horizons (black arrows), which are connected and cut by sporadic vertical canals. "Libiąż" Quarry.

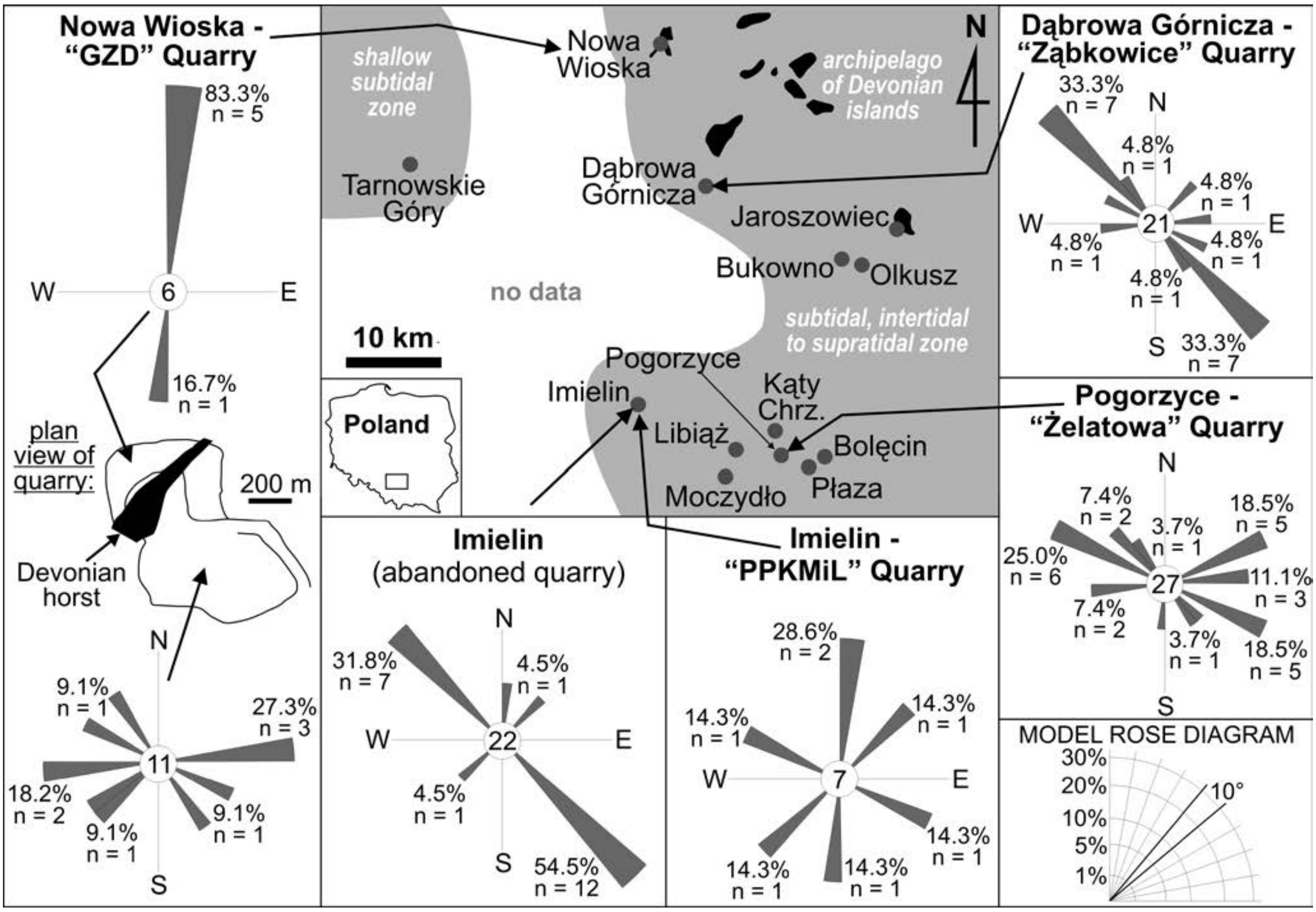

Fig. 15. Azimuths of sediment transport plotted in circular histograms. The model rose diagram is given at the bottom right of the figure. Azimuth measurements for each section are depicted in Fig. 2. Note that the NW–SE direction of sediment transport predominates in most outcrops, but was modified to roughly N–S and E–W directions by the elongated, NE–SW-striking Devonian horst, which divides the "GZD" Quarry in Nowa Wioska (and the Triassic carbonates) into two parts

The bioturbated fine-grained deposits

The bioturbated fine-grained deposits are dolomitized in most sections and occur as orange-red-brown cavernous dolosiltites with irregular spots, exhibiting a fine-crystalline microtexture. These dolomites replaced the original dark grey laminated unfossiliferous calcilutites with common burrows *Balanoglossites* and *Thalassinoides*, infilled with yellow detrital sediment and blocky calcite (Unit 1), and yellow-grey unfossiliferous, ?early diagenetic dololutites, locally containing *Thalassinoides* isp. (belonging to Unit 3 and Unit 4). Some layers are only partially altered, i.e. the coarse-grained infilling of the burrows was replaced and recoloured without changing the surrounding dark grey fine sediment (Fig. 4F). This phenomenon shows that the dolomitizing fluids initially migrated laterally *via* the complex network of burrows, from which they could have spread out to penetrate the surrounding fine deposit.

Apart from the obvious colour change and dolomitization, visible both macro- and microscopically (Fig. 16B, C), two other types of alteration are conspicuous, when the undolomitized bioturbated fine-grained deposits are compared with the epigenetically dolomitized ones. Firstly, the network of more-or-less regular burrows was replaced by irregularly spotted macrofabric (Figs 4B, C, 5A, 13A). This change presumably resulted from a selective dolomitization of bioturbated muddy deposit. To prevent the collapse of the burrows, ichnofauna impregnated their walls using organic mucus, which changed the chemistry of the muddy deposit around each burrow and resulted in the formation of distinct diagenetic haloes (Fig. 4F; Myrow, 1995; Bertling, 1999). The hydrothermal fluids, penetrating such a substrate long after lithification and reacted in a different way with its biochemically altered parts, causing a selective colour change and the development of the irregular spots. The second change is that the original non-porous fabric was replaced by vugs of different sizes. This change might have resulted from the dissolution of the blocky calcite and coarse-grained sediment, filling the burrows (Figs 4C, 16D). The dissolution process might have been already initiated during the emersion of the Olkusz Beds. However, according to Mochnacka and Sass-Gustkiewicz (1981), the bulk of dissolution was strictly associated with the epigenetic dolomitization. However, there are reports from other areas, where large vugs were created during the dolomitization process itself without any indication of dissolution (Lapponi *et al.*, 2014, with further references).

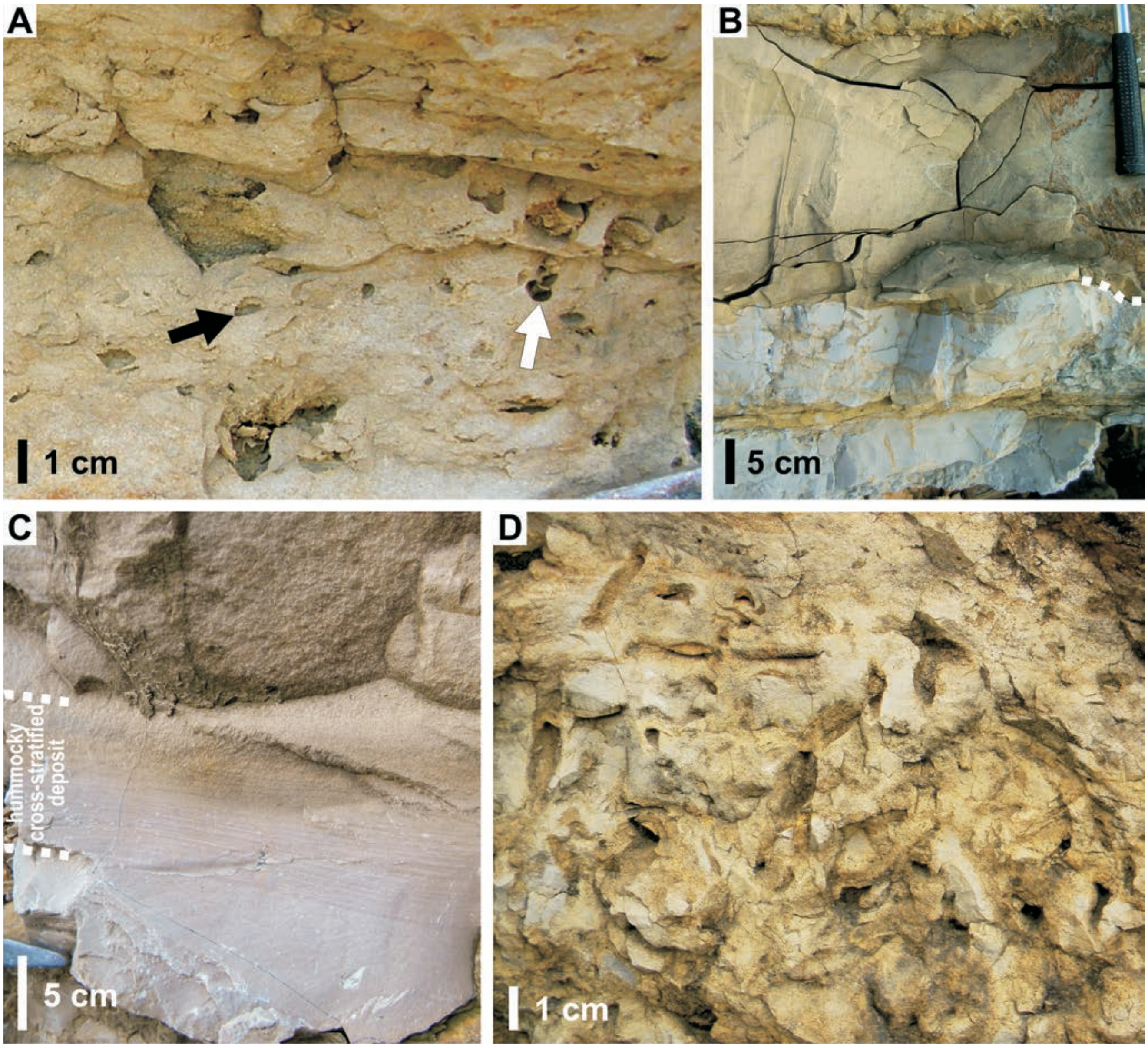

Fig. 16. Modification of original rock textures by epigenetic dolomitization. **A.** Vertical outcrop view of cavernous fabric, developed in pelolite. Note that some cavernous vugs still have the shape of bivalves (black arrow) and gastropods (white arrow). Unit 2, Nowa Wioska – "GZD" Quarry. **B.** Vertical outcrop view of limestone-dolostone boundary. Note distinct colour alteration and coarsening of primary micritic deposit. Unit 1, Pogorzyce – "Żelatowa" Quarry. **C.** Vertical outcrop view of the gradual transition from the primary grey calcilutite and hummocky cross-stratified calcisiltite to secondary orangeish coloured dolosiltite. Unit 1, Pogorzyce – "Żelatowa" Quarry. **D.** Vertical outcrop view of dolomitized ?*Thalassinoides*-bearing firmground with partially dissolved coarse-grained infills of burrows. Unit 1, Imielin – „PPKMiL" Quarry.

CONCLUSIONS

1. The name "ore-bearing dolomite" is a mining term which should no longer be used as a formal lithostratigraphic term, because epigenetic dolomitization affected various lithostratigraphic units of the Middle Triassic succession in southern Poland, and these units can be easily recognized from lithological criteria, as demonstrated in this study. These units represent consecutive evolutionary phases of the Kraków-Silesia Sub-basin (basically the transition from a regressive state, through emersion to a transgressive state). As an informal term "ore bearing dolomite", if used, should be put in inverted commas.

2. The lowermost Unit 1 is made up of *Balanoglossites* and *Thalassinoides* micritic firmgrounds, intercalated mainly with tempestitic pelolites, which were formed on the lower shoreface. The overlying Unit 2 is dominated by cross-stratified pelolites with an unknown amount of now recrystallized ooids, representing the upper shoreface and foreshore. Subsequent emersion terminated sedimentation in the region. Unit 3, capping the regional disconformity, consists of several metre-scale peritidal cycles that are composed of supratidal dolocretes, rhizolites and mudstones, intertidal cryptalgal laminites, and subtidal pelolites and bioturbated fine-grained dolostones. These lithofacies represent a tidal flat-lagoon system. The disappearance of su-

pra- and intertidal facies, resulting from a continuing transgression, marks the basal parts of Unit 4.

3. The depositional and diagenetic history of the Kraków-Silesia Sub-basin in the Anisian determined the subsequent development of the entire ore district. The clay-rich carbonate muds at the base created an impermable barrier and concentrated fluids in an interval of overlying strata, approximately 35 m thick. These strata were predominantly composed of porous carbonate grainstones-packstones and bioturbated mudstones (mostly firmgrounds). Even the bioturbated mudstones contained coarser sediment, the infilling material of the burrows *Balanoglossites* and *Thalassinoides* networks. Owing to the third-order regression, part of these deposits was subjected to subaerial exposure and meteoric diagenesis, which resulted in the development of moldic porosity. This combination of primary lithological features and diagenetic alteration favoured, during burial, the migration of dolomitizing solutions and further alteration to a potential host rock. Subsequently, the dolomitizing fluids spread laterally *via* porous horizons, such as pelolite packages or networks of burrows, which resulted in the distinct epigenetic alteration of the primary deposits. The dissolution of blocky calcite and the coarse-grained infilling of burrows, but also the enlargement of biomoldic pores, led to the formation of a massively cavernous fabric, which probably owing to further dissolution was ultimately changed into large karstic forms that host economically important ore bodies. In conclusion, the presence and distribution of porous horizons in the "ore-bearing dolomite" succession was a major lithologic control on the circulation of dolomitizing fluids in the host rock.

4. This study fills a gap in knowledge of the evolution of the Kraków-Silesia region before the epigenetic dolomitization and explains why ores and ore-bearing dolomites developed within these particular rocks. However, more detailed laboratory analysis is necessary to supplement the data and conclusions presented. The author hopes this study will initiate new investigations on the origin of Polish lead-zinc deposits that will pay more attention to the stratigraphy, composition and history of the hosting strata.

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Appendix

GPS coordinates of all outcrops presented in this study (in alphabetical order):
Bolęcin – "Skała Bolęcka" abandoned quarry (50°06'55.12"N; 19°27'45.35"E);
Bukowno – „Olkusz-Pomorzany" lead-zinc active mine (50°18'02.95"N; 19°30'05.34"E);
Dąbrowa Górnicza – "Ząbkowice" active quarry (50°22'19.75"N; 19°17'54.98"E);
Imielin – abandoned quarry (50°08'52.43"N; 19°12'13.67"E);
Imielin – "PPKMiL" active quarry (50°09'15.68"N; 19°11'42.80"E);
Jaroszowiec – "Stare Gliny" active quarry (50°21'05.62"N; 19°35'22.45"E);
Kąty Chrzanowskie – abandoned quarry (50°09'07.00"N; 19°22'27.55"E);
Libiąż – active quarry (50°06'51.28"N; 19°20'04.35"E);
Libiąż – Moczydło – "LiBet" abandoned quarry (50°05'18.67"N; 19°18'55.84"E);
Nowa Wioska – "GZD" active quarry (50°30'01.82"N; 19°12'40.37"E);
Nowa Wioska – "PROMAG" active quarry (50°30'35.20"N; 19°14'02.17"E);
Nowa Wioska – "TRIBAG" active quarry (50°30'05.32"N; 19°14'16.36"E);
Olkusz Stary – abandoned quarry (50°17'22.53"N; 19°31'08.96"E);
Płaza – abandoned pit in forest (50°06'58.46"N; 19°26'32.26"E);
Płaza – "GiGa" active quarry (50°06'24.36"N; 19°26'18.85"E);
Pogorzyce – "Żelatowa" active quarry (50°06'42.08"N; 19°23'37.56"E);
Tarnowskie Góry – "Blachówka" abandoned quarry (50°24'25.04"N; 18°51'10.83"E).