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Lofer-type cyclothems in the Upper Devonian of the Holy Cross Mts. (central Poland)

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ABSTRACT:

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Numerous horizons of carbonates changed by karstic and soil-forming processes have been recognised in upper part of the Frasnian carbonate succession in southern part of the Holy Cross Mts. These layers are included in peritidal cyclothems, characterised by mostly deepening upward pattern, similarly to the typical Triassic Lofer cyclothems. The irregular cyclothemic intervals are restricted to an interior part of the isolated, reef- and shoal-rimmed Dyminy carbonate platform. The Lofer-type cyclicity correlates with syndepositional block-faulting and associated seismic shock induced features, recognised in marginal parts of the platform. The most appropriate explanation of cyclicity is differentiated, tectonically controlled subsidence of Dyminy platform, according to the stick-slip faulting model proposed by CISNE (1986) for explanation of deepening-upward cyclicity in Dachstein Formation.

Key words: Devonian, Carbonate platforms, Syndepositional block-faulting, Cyclicity.

INTRODUCTION

FISCHER (1964) defined the meter-scale Lofer-cyclothems in the Upper Triassic Dachstein Limestone as deepening upward successions, composed of three members. Member A was an interval formed by subaerial weathering processes (paleosols); member B ("loferites") was deposited in the intertidal environment, and member C characterised subtidal deposits, the deepest in the succession. According to the original FISCHER's description the Lofer cycles originated due to the glacio-eustatic sea level oscillations, but an alternative hypothesis linking these cycles with tectonic movements (CISNE 1986) has been accepted by the discoverer (FISCHER 1986).

The observations carried out during following 35 years indicated that the deepening-upward type of cyclicity in carbonate sequences is extremely rare. Most descriptions are of Alpine-type Triassic sections (for review *see* SATTERLEY 1996 a,b; BALOG & *al*. 1997; ENOS & SAMANKASSOU 1998); only a few examples have been presented from the Devonian (ELRICK 1995, cf. CHEN & TUCKER 1999), Liassic (DOZET 1993) and Cretaceous sections (SENTENAC 1992, MASSE & SENTENAC 1987, DI STEFANO & *al*. 1997). Detailed investigations revised nearly all of the basic FISCHER's conclusions. The regularity, completeness, simplicity, and consequently deepening upward characteristics of these cyclothems have been questioned, consolidating therefore the usual shallowing-upward cyclothem paradigm in carbonate sedimentology. The crucial criticism of FISCHER's interpretation has been by ENOS & SAMANKASSOU (1998), who questioned the sedimentary nature of member A and interpreted the reinvestigated Triassic succession rather as rhythmic deposits (BCBC) than cyclic ones. No wonder that differences at the descriptive level caused the different interpretations of the origin of these successions.

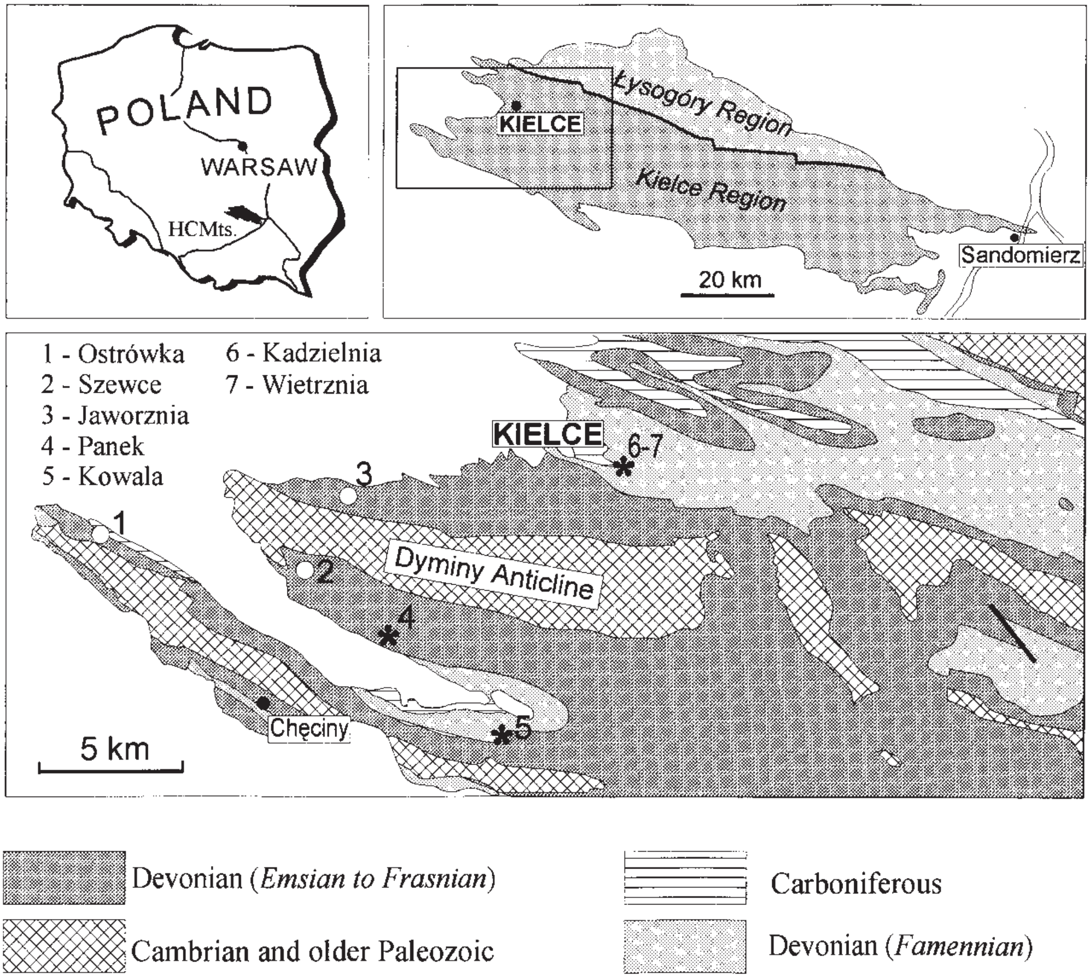

Fig. 1. Location of the Devonian sections analysed (○) or only mentioned (∗) in text on the simplified geological map of the western part of the Holy Cross Mts.

Our interest in the Lofer cyclothems appeared during analysis of processes which caused a drowning of the Middle-Late Devonian carbonate platform in the Holy Cross Mts. (SZULCZEWSKI & *al.* 1996). The uppermost part of the Frasnian Amphiporoid Limestones, investigated in the Ostrówka quarry (Text-fig. 1), revealed cyclothems very similar to those defined by FISCHER. This observation prompted us to verify the cyclicity pattern, evidenced in the Frasnian of this area by RACKI (1993). The examination of sections, exposed in numerous quarries in western part of the Holy Cross Mts., restored our belief in the reality of deepening upward cyclothems, and allowed us to estimate the paleogeographical extent of this type of cyclic sedimentation. The aim of this paper is to broaden the stratigraphic range of the Lofer cyclothem examples and to point out their possible relationship with tectonically controlled subsidence.

SETTING

The cyclic units analysed here have been found in three quarries (Text-fig. 1) where the uppermost part of the Kowala Formation is exposed (Text-fig. 2).

The quarries are located on both sides of the Dyminy Antycline, composed mainly of the Cambrian sandstones and shales. The Ostrówka W and Ostrówka N sections are measured in the large Ostrówka quarry, situated near the south-western corner of the Holy Cross Mts., at the western end of the Gałęzice hills in the southern limb of the Gałęzice-Kowala syncline. The Frasnian succession is covered here by extremely condensed crinoidal-cephalopod Famennian limestones and variable lithologically Lower Carbonifeorus succession (SZULCZEWSKI & *al.* 1996). The longer section is taken from the old western wall of the quarry, while the northern one was measured just below the edge of the

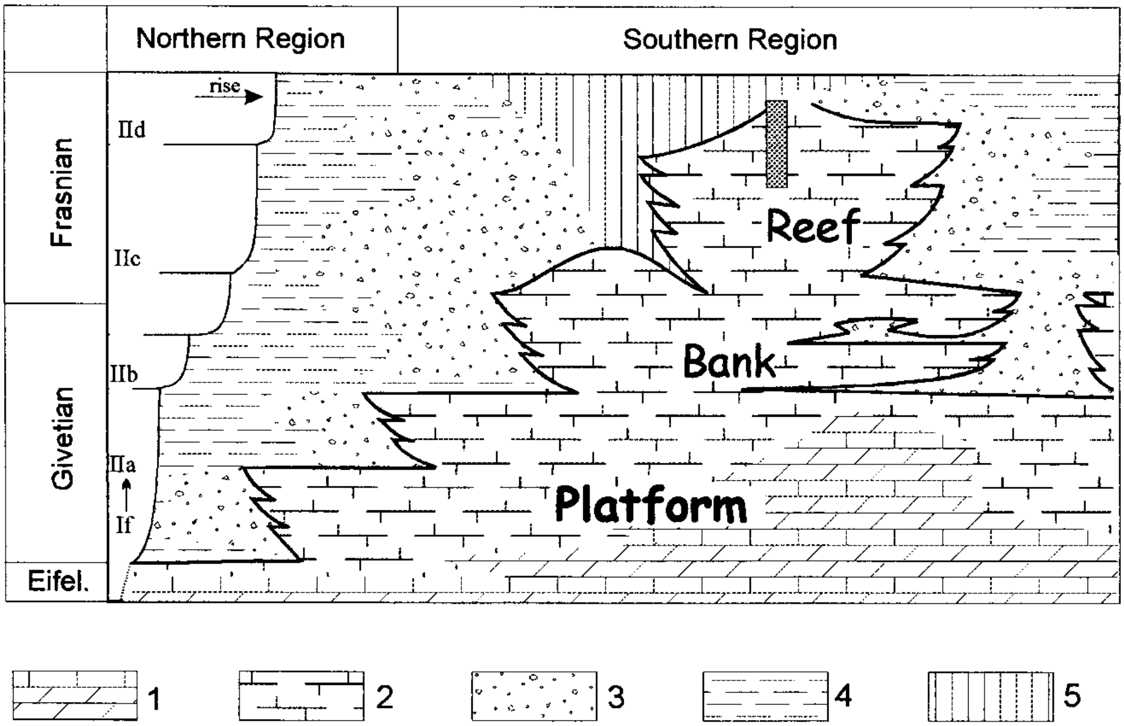

Fig. 2. Stratigraphical position of the analysed sections on the simplified scheme of the carbonate platform development (*after* RACKI 1988), related to eustatic curve of JOHNSON & *al.* (1985); 1 – dolomitic facies; 2 – platform and reef facies; 3 – detrital slope facies; 4 – open-shelf and basinal facies; 5 – hiatuses

quarry, near the exposures of the Carboniferous Limestone at the Todowa Hill.

The Szewce section is located on the western wall of the abandoned quarry on the north-eastern slopes of the Okrąglica Hill, a few hundred meters from the highway E-77. The amphiporoid-laminite complex is here similar to the lower part of the well known Panek section (KAŹMIERCZAK 1971, WRZOŁEK 1988, RACKI 1993), located in the same range of hills.

The Jaworznia sections were measured in large abandoned quarry, situated in the NW corner of the roads Kielce-Częstochowa and Cracow-Warsaw (KAŹMIERCZAK 1971). The Jaworznia W section is taken from the western wall of the quarry (comp. GŁAZEK & ROMANEK 1978, Fig. 8), whereas the northern one is located on the escarpment well exposed near the eastern entrance to the quarry.

The investigated formation (the Stromatoporoid-Coral Dolomites and Limestones from Kowala –NARKIEWICZ & *al*. 1990) embodies an extremely thick carbonate succession formed during the Eifelian, Givetian and Frasnian, and characterised by three phases of development (*cf.* KAŹMIERCZAK 1971; RACKI 1988, 1993; SZULCZEWSKI 1995). The first one, described usually as the platform phase, started with mostly dolomitic members typical of shallow subtidal and intertidal sedimentary environments. Locally, in this monotonous unit the peritidal cyclothems (PREAT & RACKI 1994, SKOMPSKI & SZULCZEWSKI 1994), and sabkha sequences (NARKIEWICZ 1991) have been recognized. The initial members of the platform were unified over the Łysogóry and Kielce regions – the two tectonically and sedimentary different paleogeographic divisions of the Holy Cross Mts, which showed individual features during nearly entire Paleozoic, but their differences developed most markedly during the Late Devonian (SZULCZEWSKI 1971, 1995).

The Middle Devonian step-by-step rise of sea level, according to pattern recognised by JOHNSON & *al*. (1985), caused changes of the paleogeographical-facies pattern of stromatoporoid-coral formation, which persisted during the gradual evolution of the platform to the bank and reef stage (RACKI 1988, 1993). The succeeding phases of transgression induced a stepwise diminishing of the area of shallow water sedimentation. Finally, it was restricted to the central part of Kielce region, particularly around the post-Caledonian high, finally uplifted in the Variscan orogeny as the Dyminy Anticline. Near the end of the Frasnian the carbonate complex was disintegrated, with locally tilted, uplifted and eroded blocks (SZULCZEWSKI 1989). In the next phase some of them were submerged, buried and covered by a stratigraphically condensed succession typical of drowned carbonate platforms (SZULCZEWSKI & *al.* 1996).

The cyclothemic units discussed here have been observed in the uppermost part of the shallow marine complex (Text-fig. 2, Upper Sitkówka Beds of older literature). The succession represents an inner, probably back-reef, lagoonal setting, dominated by vertical accretion and peritidal, restricted depositional environments (RACKI 1993). The facies show that the platform interior was most probably sheltered by a reef- and shoal-rim, although the precise position of this marginal elevations is unknown. This supposed scheme is inferred from the presence of detritic limestones outside the central part (Text-fig. 2).

Complete lack of conodonts and of the majority of open-marine benthic fossils in facies of platform-interior hinders precise determination of the stratigraphic position of the studied sections within the Frasnian and their correlation. The most relevant for this purpose are the palaeontological data from the Ostrówka quarry. The scarce ostracod assemblage with *Bairdiocypris samsonowiczi* enabled MALEC & RACKI (1993) to establish the Late Frasnian age of this section. More precise dating was afforded by foraminifers, ubiquitous in the topmost, cyclothemic part of the succession (SZULCZEWSKI & *al.* 1996). Their assemblage is markedly similar to that found by RACKI & SOBOŃ-PODGÓRSKA (1993) in some other outcrops of the highest part of the Kowala Formation, and which has been regarded as manifestation of a multilocular foraminifera invasion on a broad regional scale (cf. ZADOROZHNYJ 1987, KALVODA 1986, 1990). The assemblage is also known from other Upper Frasnian sections with age confirmed by conodonts.

The other sections discussed here are devoid of any direct palaeontological age indicators. Their precise stratigraphical position, although discussed, still remains uncertain. According to RACKI (1993) all of them occupy essentially the same position, and are slightly earlier than that at Ostrówka. RACKI correlates them within a framework of his eustatic stratigraphy, and probably on the basis of facies similarity, as equivalents of the uppermost part of the IIc eustatic cycle of JOHNSON & *al*. (1985), the top of which falls within the Early *rhenana* Zone of the Late Frasnian. Only the upper part of the Ostrówka section is positioned by RACKI in the lowermost part of cycle IId.

LITHOTYPES

The basic lithological types, amphiporoid limestones and peritidal laminites, are typical of the Givetian/Frasnian shallow marine carbonates all over the world, well known from numerous descriptions. They are classified as MF6 and MF9 microfacies by BOULVAIN & PREAT (1987) in the classical Devonian sections in Belgium, or varieties of SMF 6 (D11) and SMF19 (D13) according to scheme of Standard Microfacies proposed by WILSON (1975).

The facies end-members of the "Amphiporoid Limestones", predominating in the sections, are calcispherid wackestones and amphiporoid floatstones. Commonly the intermediate types are observed: calcispherid-gastropod packstones/wackestones with rare amphiporoid sticks (Pl. 2, Fig. 3; Pl. 4, Figs 4-5) or amphiporoid bafflestones. Subordinate elements include peloids, tubular calcareous algae (palaeoberesellids), ostracods, multilocular foraminifers, rare crinoids, and oncoids. The tabulate corals are extremely rare between macrofaunistic elements. Large massive stromatoporoids, as well as rare megalodontid bivalves are scattered throughout the layers. The limestones beds are usually 30-100 cm thick.

Laminitic layers are considerably thinner than the amphiporoid layers and display flat, regular lamination. Only sporadically small stromatolites were observed. In a few layers, flat-pebble conglomerates or thin intercalations of intraformational fine-grained breccias have been found. Diverse fenestral structures, especially common in the topmost part of the sections complete the appearance of the lithotype. The microfacies is composed of peloidal laminae with rare calcispheres, alternating with sparfilled fenestrae, rarely with continuous laminae, probably of microbial origin (Pl. 1).

Both these lithotypes comprise characteristic pairs of units, deposited in peritidal sedimentary environments (e.g. READ 1973, HAVARD & OLDERSHAW 1976, WONG & OLDERSHAW 1980, PREAT & MAMET 1989, RACKI 1993, ELRICK 1995). The amphiporoid-calcispherid facies with extremely impoverished biotic assemblage, well defined in the Devonian sedimentary environments are usually interpreted as lagoonal, shallow subtidal sediments (*cf.* JANSA & FISCHBUCH 1974, LARSEN & *al.* 1988). The specific content of faunal assemblages, typical of restricted environments, is most probably related to abnormal salinity. Traditionally it was interpreted as hypersaline, but this is contradicted by a general lack of evaporites in the succession. Hence, a lowering of salinity and its dramatic changes, as well as variations of temperature seem to be the more probable factor, decisive in development of specific biocenosis (cf. remarks on stromatoporoids – KAŹMIERCZAK 1971, ŁUCZYŃSKI 1998, and some brachiopods – RACKI 1986; compare also more far-reaching conclusions on the peculiarity of the calcisphaerid-amphiporoid facies presented by KAŹMIERCZAK & *al.* 1985).

In respect to the Lofer cyclothems, the amphiporoid facies described here corresponds to the megalodontid limestone, representative of unit C in the Dachstein Limestone. Although the biotic diversity in Dachstein facies is decidedly greater than in the amphiporoid one, the megalodontid facies is commonly interpreted as "subtidal deposits with little restriction in circulation" (review *in* ENOS & SAMANKASSOU 1998). This conclusion is generally proper to the "Amphiporoid Limestone", but the level of "restriction" is evidently higher than in the Triassic example.

Laminated and fenestral members are typical of intertidal environments (see comprehensive discussion *in* BOULVAIN & PREAT 1987), and they evidently resemble the loferites (unit B *in* FISCHER's classification). Both members are usually bound together in the shallowing-upward cycles extensively reported from different Devonian platforms and known also from the initial part of the platform succession in the Holy Cross Mts (PREAT & RACKI 1993, SKOMPSKI & SZULCZEWSKI 1994).

Contrary to these commonly appearing facies, the third lithotype, regolith with paleosols, is rarely described from successions older than Carboniferous, because its more common development is directly stimulated by plant vegetation. The horizons with evidences of subaerial weathering processes firstly have been recognised in the Ostrówka section. RACKI (1993) and SZULCZEWSKI & *al.* (1996) connected them with paleokarstic features. In the very short, and precisely analysed section near Todowa Hill (Ostrówka N in this paper) SZULCZEWSKI & *al.* (1996) distinguished generally two different types of such layers: rubble zones and horizon of solution pipes. The present observations indicate that the occurrence of solution pipes is exceptional, and they are absent from other sections (detailed description *in* SZULCZEWSKI & *al.* 1996). However, the regoliths are recognised in Ostrówka N section in only two horizons; other intervals are more frequent and differently developed and enriched in features typical of carbonate paleosols.

A thickness of the rubble zones only locally reaches 40 cm (Pl. 1, Figs 3-4, 6; Pl. 2, Figs 1-2), but they are easily distinguishable due to their red or green coloration. Bottom boundaries of these horizons are gradual and indistinct, similar to the typical regoliths. The horizontal extent of the levels, observable in the quarry, does not exceed 80 m. The rubble consists of host-rock clasts, mainly calcispherid wackestones, or single amphiporoid sticks, when the rubble layer is developed on the amphiporoid floatstones (Pl. 2, Fig. 2; Pl. 3, Fig. 1; Pl. 4, Fig. 4). Clasts generally have irregular, but rounded margins and range in size up to several centimetres. Sometimes, they are covered by micritic or laminated coatings, but there are also layers which resemble fine grained breccias (Pl. 3, Figs 4-5). At least three types of specific cements are observed in these horizons. Most characteristic are stalactitic ones (SZULCZEWSKI & *al.* 1996, cf. HAVARD & OLDERSHAW 1976), which are recognisable even in the case of strong recrystallization, due to their specific pendant form (Pl. 2, Fig. 3; Pl. 4, Fig. 4). Typical are also blocky yellow-brown cements, coloured by organic compounds (Pl. 4, Fig. 3). A third type, drusy cement with rounded crystals coated with characteristic ferruginous rims, is very rare and it has been found only in fine-grained brecciated beds. The matrix of regoliths is a red to green marly clay. The amount of argillaceous material in the matrix is relatively large, but probably it is only residual, because no quartz grains occur within it.

In a few places the uppermost part of regoliths is laminated. The lamination sometimes is clearly mechanical, connected with thin intercalations of detritic material, but in other cases this is a typical laminar calcrete developed as dark-brown or even black thin layers, with contorted microbial millimetre-scale lamination (Pl. 3, Figs 1-2; Pl. 4, Figs 1-2). The laminae exhibit small microborings and enclose large peloidal glaebule. Locally the laminae are ripped by desiccation cracks, and small fragments of calcrete are included into fissures infilling. In other sections the analogous of laminar calcrete appeared as coatings on clasts. The laminar calcrete layers are very similar to those described by ADAMS (1980), WRIGHT (1982), PASZKOWSKI (1986) and DAVIES (1991) from the Early Carboniferous carbonates. However, in the Devonian examples there are no traces of typical alveolar structure or other rhizolithic features.

The features presented, typical of described horizons, show that the development of the rubble zones evidently resembles weathering of bedrock, cementation in the vadose zone, and finally formation of paleosols. The investigated rubble is closely related to those described by MEYERS (1988) from the Mississippian carbonates in New Mexico, who regarded them as a subsoil paleokarstic product. Similar rubble zones with analogous interpretation were reported from the Lower Carboniferous of Wales by WRIGHT (1982, 1988) and DAVIES (1991). In the Carboniferous examples the thickness of the weathered zone is substantially greater and attains several metres. Although the Devonian development of terrestrial floras was significantly accelerated (e.g. ALGEO & SCHLECKER 1998, WILLIAMS & KRAUSE 2000), in comparison with the Carboniferous, the Devonian paleosols were still weakly developed. The paleosol horizons described here have been found in few places, but it seems probable that some of them have been eroded during the submergence of previously uplifted places. Anyway, the elements of the paleosol cover indicate that the process of formation of the described intervals could be interpreted rather as soil weathering than purely karstification, which precisely indicates semi-arid/humid climate, according to the schemes proposed by WRIGHT (1988, 1994). This conclusion, concerning the climate of the Frasnian in the Holy

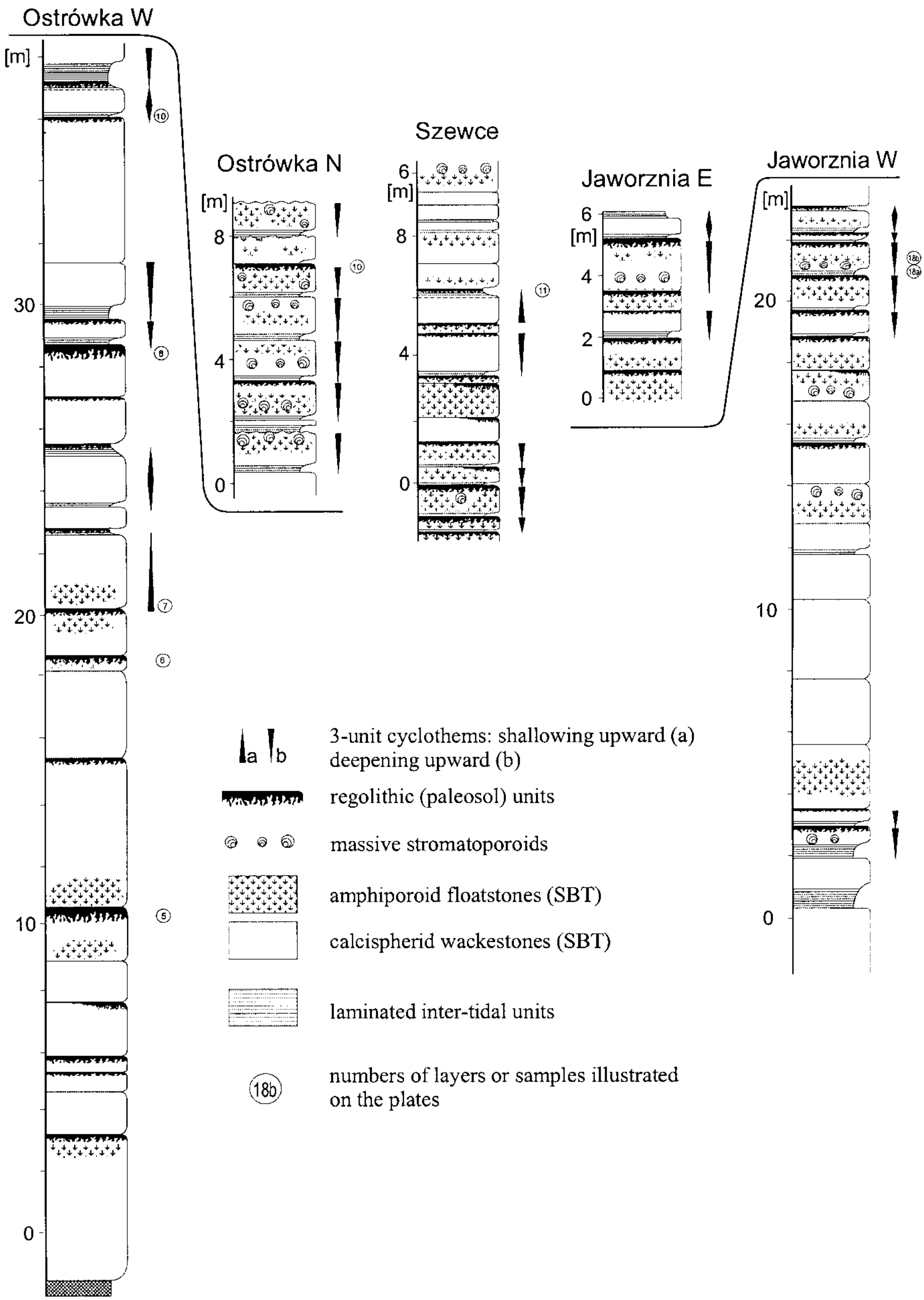

Fig. 3. Distribution of cyclothemic units in the Frasnian sections in the Holy Cross Mts.

Cross area is also supported by RACKI's (1986, 1993) arguments, based generally on the lithology and fossil content of the Kowala Formation.

The pipe level is interpreted in SZULCZEWSKI & *al.* (1996) as analogue of recent *kavornossen karren*, a distinctive feature of tropical karst (WRIGHT 1982, 1988). However, in the present state of exposure it seems that these cavities have been formed below a cover of laminites, and some parts of them collapsed later into them [similar features have been described by DAVIES (1991)].

The paleosol intervals correspond exactly with FISCHER's member A, described originally as greenish grey, ochreous-brown or brick-red units of argillaceous limestone, with a sharp upper boundary.

SUCCESSION OF LITHOTYPES

The investigation of the Ostrówka N section (SZULCZEWSKI & *al.* 1996) indicated a very regular appearance of lithotypes, with a pattern resembling the typical Lofer cyclothems. Seven deepening upward cyclothems have been distinguished, with an average thickness of 1.2 m. The regolithic units have been found only in two cyclothems, but in other cases the sharp erosional top-surfaces, suggest removal of weathered units (*see* wedging horizon *in* RACKI 1993, Fig. 38A). The boundaries of cyclothems have been placed on these surfaces or between the subtidal and rubble units, it means in place of "facies skip", in relation to the complete symmetric succession in perilittoral carbonate environments.

The extension of observations to the other sections shows that this pattern is not simple and unequivocal. In the measured successions (Text-fig. 3) the regolithic or paleosol units are rather irregularly scattered, and only a half of them have been found in more or less complete,

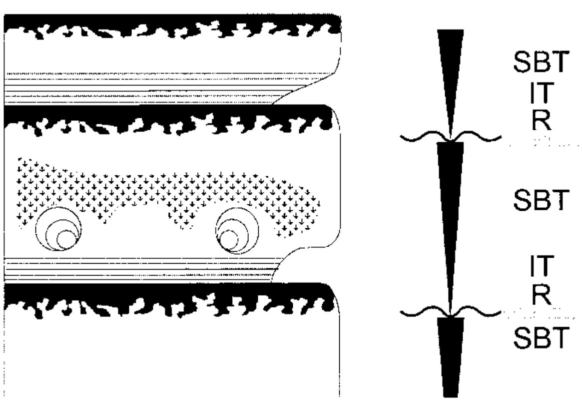

Fig. 4. The modal succession of microfacies in the Frasnian cyclothemic units ; *SBT – subtidal units; IT – intertidal units; R - regolithic units*

tripartite cyclothems (Text-fig. 4). Only 28 complete cyclothems, composed of at least 3 units (subtidal, intertidal, supratidal) have been distinguished in the analysed sections (displayed on the Text-fig. 3). Most of them are deepening upward ones (22); 4 cyclothems are nearly symmetric; 2 of them are shallowing upward. The most regular and complete cyclothems are usually grouped in some intervals of the analysed sections. Other regolithic units, which are not located in regular cyclothems, usually terminate subtidal intervals, which are very diverse in thickness (several tens of centimetres to more than 10 meters).

ORIGIN OF CYCLOTHEMS

In any case, taking into account the statistical outcome as well as direct observations of cyclicity, an asymmetric nature of the process responsible for formation of the Frasnian succession is clear. Its most common feature was the steady deepening of depositional environment, followed by brief episodes of rapid shallowing. In this sense the succession is analogous to the cyclic Triassic limestones, but it differs in smaller number of repetitive cyclothems and irregularity of cyclicity. In other features, such as a lack of neptunian dykes and horizontal sheet cracks, it differs from the typical Lofer cyclothems. However, the analogous facies spectrum and their specific successions are so similar that we decided to qualify the recognised cyclothems as Lofer-type ones. Their nearest analogue seems to be the "transgressive-prone exposed subtidal cycles" described from marginal part of the Middle Devonian ramp of the Eastern Great Basin in North America, which are usually "composed of (...) tidal-flat laminites gradationally overlain by shallow subtidal facies (burrow-mottled or *Amphipora*-rich subfacies)", and terminated by interval with dissolution cavities filled with clay-rich residuals and breccia clasts (ELRICK 1995). This type of cyclothem is relatively rare in broad spectrum of cyclothems observed by ELRICK (1995), and, what is striking, located only along the ramp margin, within the maximum flooding zone of particular sequences.

The presence of subaerial weathered units in cyclothems allows one to preclude the autogenic mechanism of cyclicity (cf. STRASSER 1991, HARDIE & *al.* 1986, ELRICK 1995, SATTERLEY 1996a, 1996b). Although in the case of the discussed cyclothems, the depth of substrate penetration by meteoric fluids during soil formation episodes was not greater than several tens of centimetres, it is impossible to assume that a relative drop of sea level below the surface of platform resulted from tidal-flat progradation. Hence, it remains to estimate the relative influence of the two commonly considered factors: tectonics and eustasy, on cyclothem formation. On the other hand, this interpretation should take into account the particular paleogeographic location of the sections (internal part of platform), stage of platform development (termination), and the stratigraphical position of cyclothemic units (Middle-Upper Frasnian).

The vertical pattern of the cyclothems studied here is generally irregular, and it does not reveal any correlative potential, even on a very short distance (pinching-out of regolithic units is visible on the northern wall of the Ostrówka quarry). This feature seems to be decisive for the exclusion of a eustatic cause for the cyclicity. However, the computer simulations of eustatically controlled cyclicity presented by GOLDHAMMER & *al.* (1990) indicate a specific repetitive arrangement of smaller cycles in longer megacycles of higher order and absence of some cycles in stratigraphical record. Generally, thinner cyclothems are grouped in the topmost part of megacycles and they are associated with thicker exposure caps. The appearance of the Frasnian regolithic units in groups, after intervals of section devoid of this feature (visible in longer sections of Ostrówka and Jaworznia, *see* also Text-fig. 4 *in* SZULCZEWSKI & *al*. 1996), corresponds in some respects with the model results. It should be also noticed that tapering of regolithic units over small distance indicates that the sedimentary record is incomplete, but thickness of removed deposits is relatively small. This feature is more significant for the recognition of individual cyclothems, than for overall thickness of lagoonal formation.

A more significant argument against a eustatic cause of cyclicity seems to be the estimation of subsidence (and infill sedimentation), as well as sea level change rates. The data quoted by RACKI (1993, p. 132) point for several times faster sedimentation in area of reef than in more basinal detritic limestone (35 m thick deep foreslope complex is considered as time-equivalent of 230 m reef-interior member). It seems therefore that the effect of the eustatic changes would be completely masked by effects of subsidence, and keeping-up sedimentation.

The arguments for tectonic cause of cyclicity arise rather from an analysis of the regional development of the Frasnian in southern part of the Holy Cross Mts. than from detailed sedimentological observations. CISNE (1986), FISCHER (1986), HARDIE & *al.* (1986), and in some respect SATTERLEY (1996a, 1996b), emphasised a significant influence of tectonic movements on the cyclicity of Triassic Alpine sedimentation, especially regarding deepening upward cyclothems. The fundamental difficulty in accepting this hypothesis, which combines each cycle with single tectonic impulse, is the necessity of numerous and regular recurrences of tectonic movements to explain a formation of very long cyclic successions. The proposed "yo-yo" tectonic model (CISNE 1986) assumes the periodical discharge of stress, which originated in the transitional area between platform and quickly subsiding basin, associated with stick-slip faults. This process causes cyclic stops of platform subsidence or even its short negative vector (uplift, see CISNE 1986, Fig. 1b). It is obvious that the sedimentary record of this recurring process should be readable close to the platform margin, in the form of cyclothems. It should be noted, however, that in the case of rimmed platforms the preservation of cyclothems with complete facies record in the barrier zone is rather difficult and uncommon.

The Middle Devonian cyclothems described by ELRICK (1995) fulfill exactly this condition, but the author excluded this hypothesis, because of data which contradict the expected tectonic style in the Devonian of west-

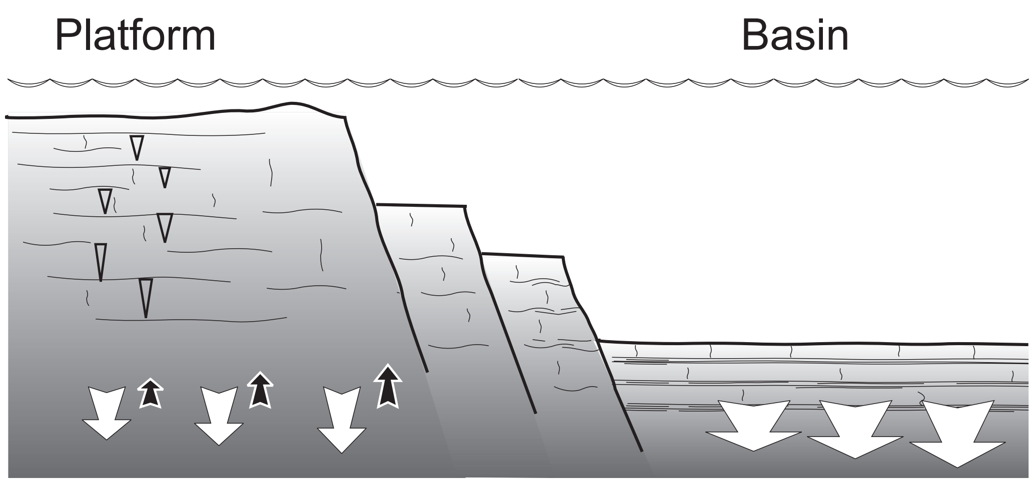

Fig. 5. Idealised diagram illustrating an influence of stick-slip faulting on the sedimentation in the marginal part of carbonate platform

Oscillatory subsidence of platform (greater one during the phase of stress increase – white arrows, and smaller one or even negative after the relaxation – black arrows at the left part of the scheme) and monotonous subsidence of the basin (white arrows at right part of scheme) ern North America. The presence of marker beds, extending over 100 km, and 3rd order depositional sequences correlative across the entire ramp and within the basin, were considered the arguments against tectonic cause of the observed cyclicity.

Contrary to the above mentioned interpretation in the Frasnian example described here the tectonic model seems to be very convenient to explain the process of cyclic sedimentation (Text-fig. 5). Although a shallow-marine carbonate deposition persisted in the Holy Cross Mountains from the Eifelian to the lower Famennian, a meter-scale, deepening-upward cyclicity is confined to its Frasnian stage, when the depositional system became a reef- and shoal-rimmed isolated platform (Dyminy Reef Complex of NARKIEWICZ 1988). In its earlier stages, when this area was not distinctly discriminated from the surrounding broad carbonate shelf of low-relief morphology, cyclic deposition also developed temporarily and locally, but those cycles mostly exhibit shallowing-upward environments (NARKIEWICZ 1982, PREAT & RACKI 1993, RACKI 1993, SKOMPSKI & SZULCZEWSKI 1994).

The deepening-upward cyclicity described here is restricted to the spatially dominating interior of the isolated Frasnian platform. The Frasnian-Famennian stratigraphic records at the southern and northern margins of the platform both reveal a large-scale deepening-upward depositional evolution which is not known from its interior, although they differ substantially in facies. Such a general direction in environmental evolution reflects progressing drownings and backsteppings at the platform margins. A dispute exists as to what extent a shrinkage of the platform and depositional evolution were influenced by eustasy and tectonics (SZULCZEWSKI 1989, 1990; NARKIEWICZ 1990; RACKI 1991; NARKIEWICZ & RACKI 2000), but a share for faulting in its drowning is obvious.

The northern belt of marginal facies, relatively widely exposed in the Kadzielnia chain of hills (e.g. Wietrznia and Kadzielnia quarries in the centre of Kielce town), provides more evidence of syndepositional faulting and associated earthquake activity in the Frasnian, than the more concealed southern one. CISNE (1986) assumed that fault-induced deepening-upward cyclicity could develop up to a distance of 20 km from the faulted margin of the Dachstein carbonate platform, so the width of the Dyminy platform well falls within this limit. Hence, the Dyminy platform was narrow enough that faulting activity at any of its margin could resulted in cyclic deposition over its entire interior.

A position of the southern faulted margin of the carbonate platform is inferred from the sharp facies contrast with the adjacent intra-shelf basin, and from the thick marginal wedge of calcirudites encountered in the borehole Kowala 1 (ROMANEK & RUP 1990). The low-angle unconformity truncating the Frasnian cyclic interval in the Ostrówka quarry and capped by the Famennian condensed sequence after pronounced time lag seems to be developed over a fault bounded tilted block (SZULCZEWSKI & *al.* 1996). At the northern margin, progressively more deep-water deposition encroached stepwise upon the rim of the platform in the Frasnian and the early Famennian, probably as a combined effect of eustasy and faulting.

The Frasnian of the northern platform margin also shows pronounced lateral and sharp changes in thickness, stratigraphical completeness and facies. This differentiation was largely controlled or affected by syndepositional block-faulting. Faults throws are from several decimetres (Kadzielnia quarry), through several metres up to about 80 metres (Wietrznia quarry). Displacements of several meters range, hence similar amplitude to those which according to CISNE (1986) generated cyclicity within the Dachstein platform, are to be directly observed and their effect on deposition and stratigraphy could be precisely estimated at the Wietrznia quarry (SZULCZEWSKI 1989).

The oldest recognized faults influenced deposition in the *transitans* Zone of the early Frasnian, but some small synsedimentary faults developed in the Early *rhenana* Zone of the late Frasnian. Also the pattern of thickness within the condensed deposits of the Famennian pelagic platform, which covered the shallow marine platform after its drowning, was affected by small-scale syndepositional faulting (SZULCZEWSKI & *al*. 1996).

Other effects of the Late Devonian extensional tectonics within the carbonate platform are numerous neptunian dykes. They are concentrated in the marginal portions of the platform, whereas they are exceptionally rare in its interior. Conodonts obtained from fissure fillings enabled the recognition that the fissures opened in several episodes over a long time span, ranging from the *rhenana* Zones of the Frasnian up to the Tournaisian (SZULCZEWSKI 1973, 1981).

Moreover, several sedimentological features of marginal belts of the Frasnian platform may owe their origin to seismic shocks. First of all there are flat pebble conglomerates, synsedimentary folds and zebra rocks. Flat pebble conglomerates appear within slope deposits on both sides of the Frasnian platform and are sandwiched within the intra-shelf basinal succession, which covered the drowned shallow-marine platform early in the Famennian (SZULCZEWSKI 1968, 1971, 1989; KAŹMIERCZAK & GOLDRING 1978; BIERNAT & SZULCZEWSKI 1993). The oldest known horizons of conglomerates occur no higher than in the *punctata* Zone of the early Frasnian, and the youngest in the Late *crepida* Zone of the Famennian, but they seem to be more common in the late Frasnian and close to the

Frasnian/Famennian boundary. Slumping (SZULCZEWSKI 1968), storm action or tsunami (KAŹMIERCZAK & GOLDRING 1978) and cohesive debris flow (BIERNAT & SZULCZEWSKI 1993) were proposed as the main agents for reworking and transportation of flat pebble conglomerates, but earthquakes were invoked as initiating the formation of these deposits (SZULCZEWSKI 1968, KAŹMIERCZAK & GOLDRING 1978) and other structures regarded as submarine slumps in the Upper Devonian of the Holy Cross Mountains (RADWAŃSKI & RONIEWICZ 1962).

Zebra rocks are known to occur usually within biolithites, but here thick sets of this fabric are extensively developed in the pelagic member (Manticoceras Limestone), which was deposited upon the northern margin of the drowned shallow-marine platform late in the Frasnian (mostly in the Early *rhenana* Zone). An association of zebra structures with small- to medium-scale block-faulting and particular mechanical deformations in their structure strongly suggest that their origin was also initiated by seismic shocks.

RACKI & NARKIEWICZ (2000) suggested that several other coarse grained intercalations within the platform slope and basin deposits of the Frasnian and early Famennian were possibly also induced by tectonic instability.

Timing of block-faulting and possible earthquake recorded in the stratigraphical succession of carbonate platform and its surrounding is much more precise than the dating of the sequences composed of deepening-upward cycles. Nonetheless, the cyclic intervals fall within a long time span of documented extensional tectonics activity, encompassing the almost entire Frasnian, and rather within its upper part, characterised the climax of this activity. This coincidence makes an application of the CISNE (1986) model for stick-slip fault generated cyclicity to the Dyminy carbonate platform convenient and justified.

According to the tectonic model of CISNE (1986) and to the paleogeographical circumstances described above, the paleosol horizons were formed during abrupt episodes of stopped subsidence on the platform. The minimal fall of sea level (eustatic ?) was sufficient for the development of exposure surfaces, shallow karstic processes or paleosol development. The return to "normal" subsidence, constrained by the quickly deepening neighbouring basin, caused the formation of a deepening succession, terminated by the next exposure surface.

FISCHER (1986) generally accepted this explanation of the Lofer-type cyclicity, however, he noted the problem of bathymetry of the Hallstatt basin, limiting the Dachstein platform from the south. If the model would be useful, the basin should have subsided more than the thickness of platform carbonates (~1500 m), which implies a relatively great depth of sedimentation. In our example this difficulty is less significant, because the deepening upward cyclothems appeared over a short interval (maximum 100 m thick). It is easy to explain the few hundred metres depth of the basin, which was necessary to pull down the platform margin. The subsiding basin was infilled with marly facies deposited in poorly oxygenated conditions, and its origin was nearly coincident with reef-phase development (SZULCZEWSKI 1971, 1979; RACKI 1988, 1993).

The tectonically-induced cyclicity model also explains the paleogeographical position of the Lofer-type cyclothems, which in the quoted above Triassic example have been found in the external part of platform, but not in their most marginal edges. This position well corresponds to the assumptions of the presented model, which takes the dying out of the cyclicity away from the platform's margin (CISNE 1986). In the most external, reefal (barrier) parts, which were evidently stronger tectonically affected, the sedimentary record of the tectonic movements comprises more dynamic processes (compare CISNE 1986, Fig. 1b), as for example a development of the neptunian dykes, conglomerates or simply erosion. In this context a possibility of undisturbed paleosol development and preservation existed only in lagoonal environments.

A metre-scale, peritidal cyclic deposition is commonly regarded as a sedimentary response to orbitally forced sea-level oscillations. The example described here does not preclude such interpretation, but it also does not provide any positive evidences to confirm it, such as Milankovitch-type cycle ratio, or a widespread lateral persistence of individual cycles. On the contrary, there is a striking time-coincidence of cyclic deposition with several sedimentary features, which seem to be induced by syndepositional faulting. Hence, the stick-slip faulting cause for the Lofer-type cyclicity, as proposed by CISNE (1986), is considered as the most conceivable also for the Devonian example.

CONCLUSIONS

1. Brecciated, red-greenish rubble intervals, which appeared in the Frasnian, in the topmost part of the Stromatoporoid-Coral Formation (Kowala Fm.), originated during emergence episodes of carbonate substrate and were changed by karstic and soil-forming processes.
2. These horizons most commonly cover shallow subtidal deposits, and are followed by typical intertidal deposits. The modal succession: paleosol – intertidal – subtidal was repeated in irregular periods and composed the deepening-upward cyclothems, which are analogous to the Lofer-cyclothems from the Alpine Triassic.

3. The lowering of sea-level below the sedimentation surface, needed for the creation of cyclothems, excludes an autocyclic mechanism of sedimentation. In the course of nature, the irregularity of observed cyclicity and lack of correlative potential of the small-scale cycles does not support a eustatic cause of the repetitive sedimentation.
4. The most probable explanation of the Frasnian cyclothems origin is tectonical control of the carbonate platform margin by a quickly subsiding basin. This hypothesis is in agreement with the assemblage of extensional tectonic features well known in the southern (Kielce) part of the Holy Cross Mts.

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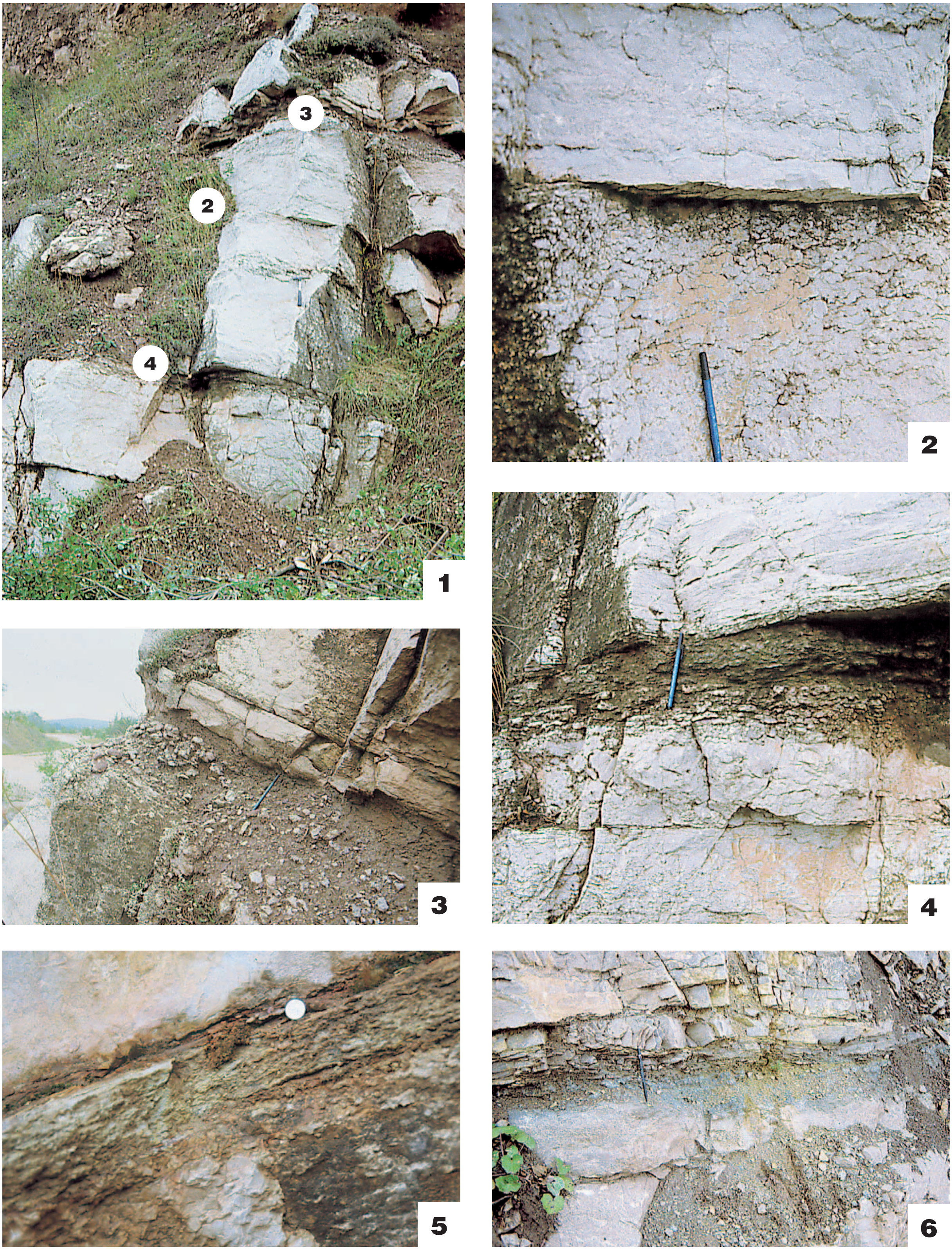
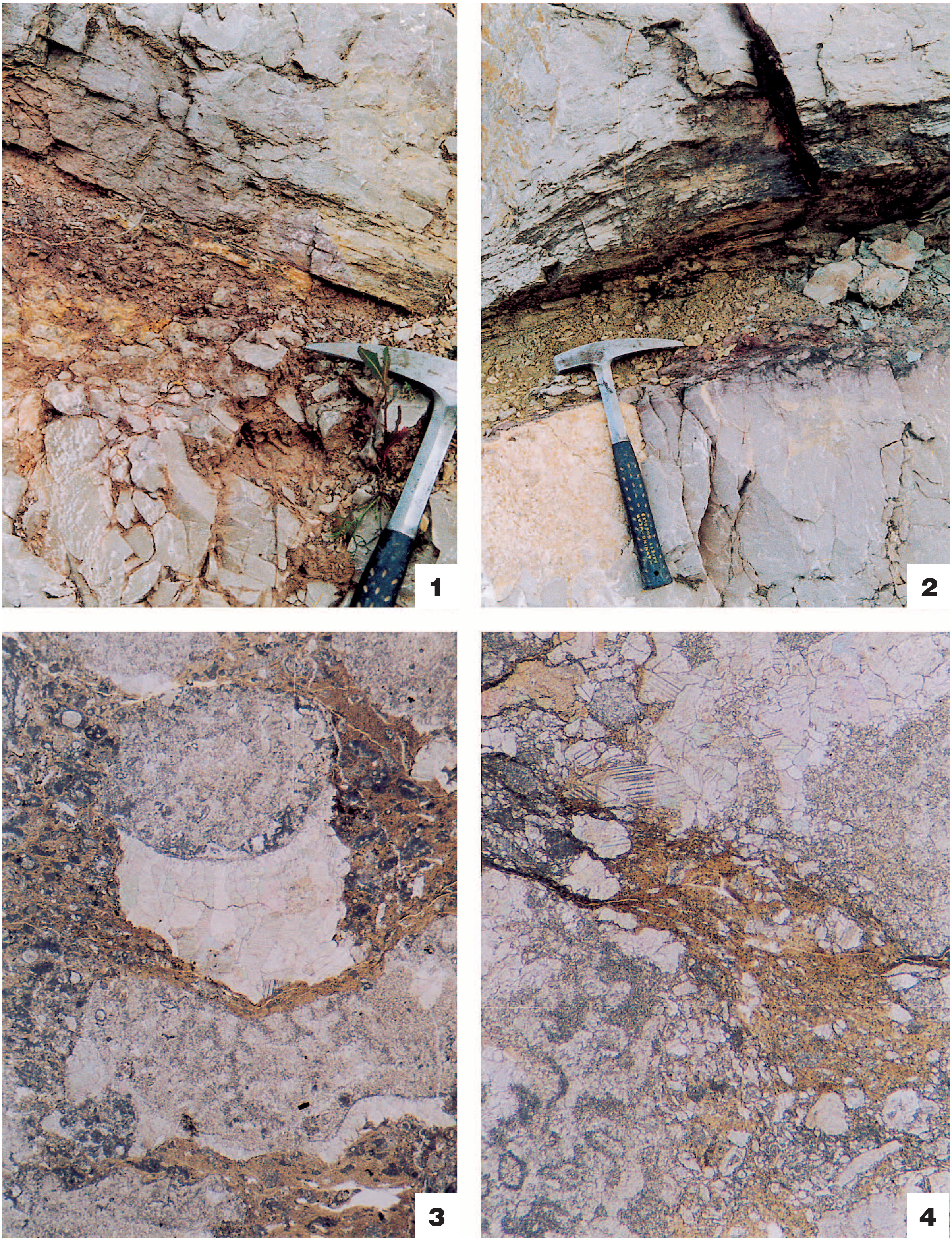
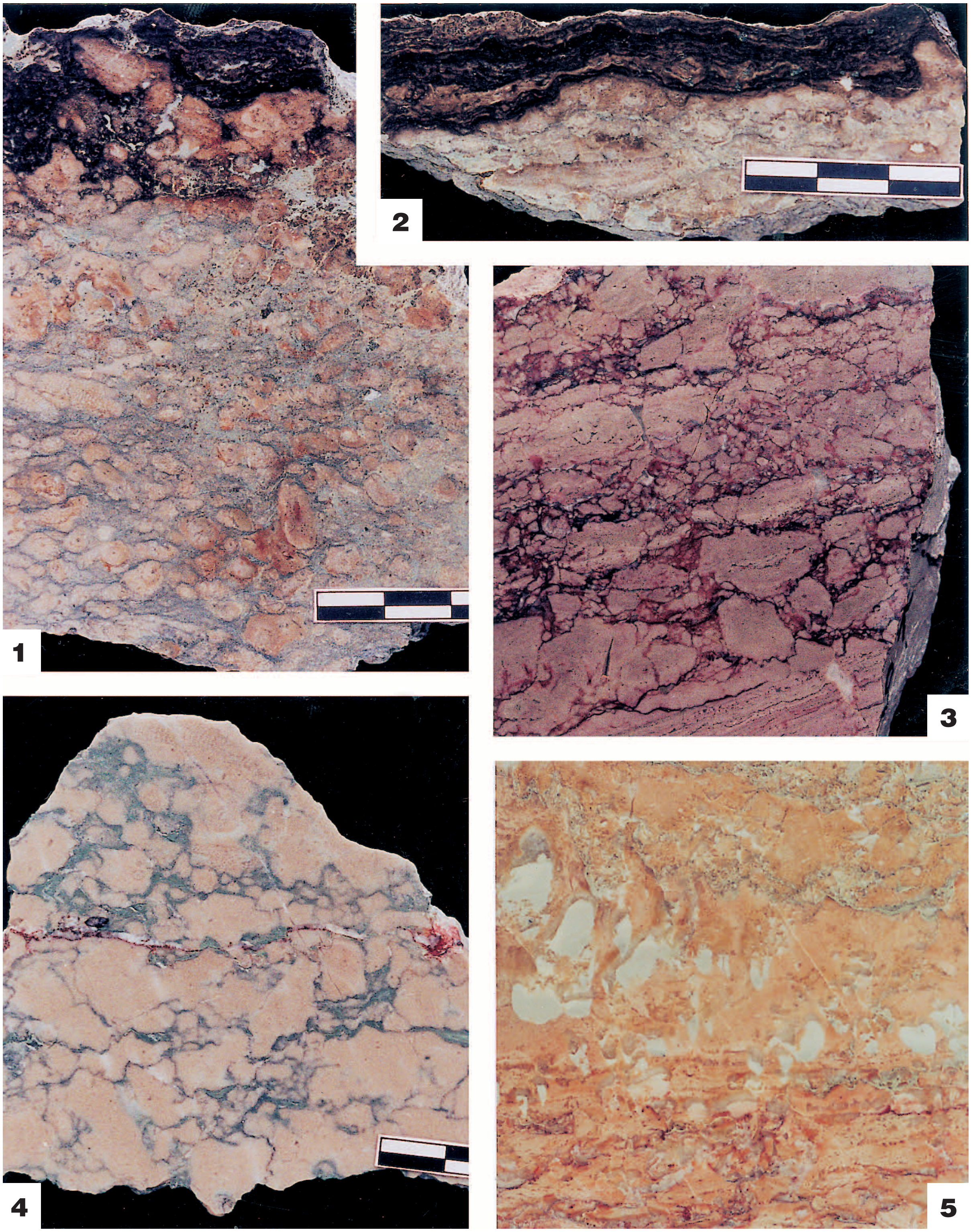


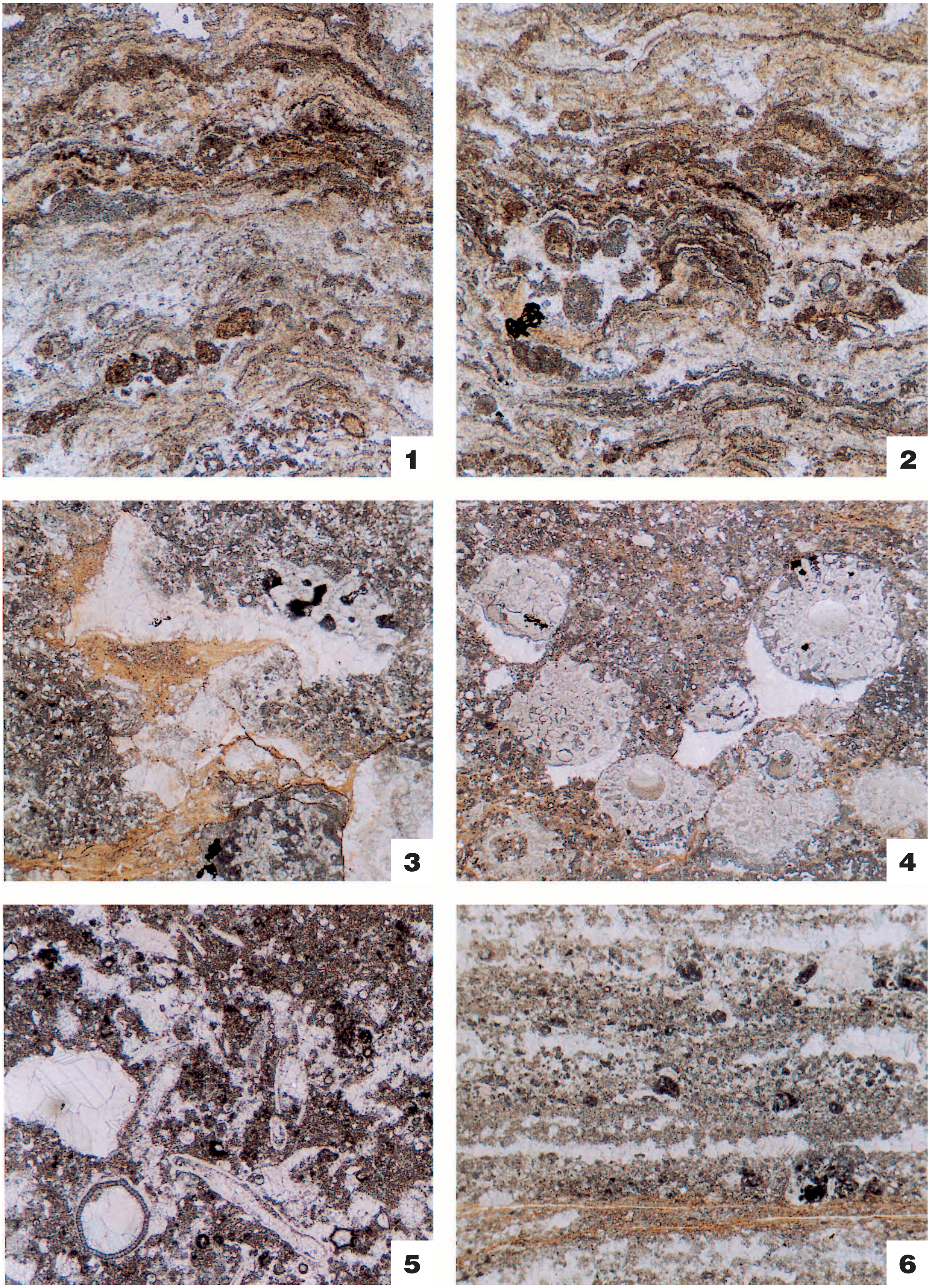
1 – Fragment of the cyclothemic succession in the Jaworznia quarry; section Jaworznia E; numbers in circles indicate boundaries of cyclothems illustrated on the photos 2-4; **2-4** – Details of regolithic units in cyclothems illustrated on the photo 1; **5** – Upper boundary of shallowing-upward cyclothem; laminated and weathered intertidal deposits covered by calcisphaerid-amphiporoid subtidal layer; Szewce quarry, sample 11; **6** – Boundary of cyclothems in the northern wall of the Ostrówka quarry (lowermost level): blue-green regolithic units covered by intertidal laminites (layer correlated with Ostrówka W/5)



1-2 – Details of cyclothem boundaries in the western wall of the Ostrówka quarry: regolithic units covered by intertidal laminites; (1) - layer Ostrówka W/5; (2) - layer Ostrówka W/6; **3-4** – Thin sections from the regolithic units; Ostrówka quarry: marly-ferruginous matrix, amphiporoid clasts with microstalactitic pendant cements are visible; sample Ostrówka 10; × 12



1-2 – Paleosoil crusts with lamination and glaebules developed on the regolithic units formed on the amphiporoid limestone: northern wall of the Ostrówka quarry (lowermost level); layer correlated with Ostrówka W/5; **3-4** – Fragments of brecciated regolithic units: sample Ostrówka W/10; **5** – Transition from the intertidal unit with loferitic fabric to the regolithic unit with small cavities (burrows ?, paleokarst ?) infilled with vadose silt; microstalactitic cements crown nearly each cavity: northern wall of the Ostrówka quarry (lowermost level); layer correlated with Ostrówka W/5



1-2 – lamination and glaebules typical of paleosol crusts illustrated on the Pl. 3/1-2; thin-section; × 20; **3-4** – microstalactitic and blocky cements within regolithic units developed on the amphiporoid limestones; (3) thin section Ostrówka W/6; × 10; (4) thin section Ostrówka W/7; × 7; **5** – calcispherid wackestone with *Cribrosphaeroides* - typical subtidal microfacies in the studied sections: Jaworznia E section, sample 18; × 25; **6** – laminated intertidal unit with laminar fenestral fabric; Jaworznia E section, sample 18a; × 20