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Dolomitic paleosols in the lagoonal tetrapod track-bearing succession of the Holy Cross Mountains (Middle Devonian, Poland)

Marek Narkiewicz [a,*], Gregory J. Retallack [b]

[a] Polish Geological Institute-NRI, 00-975 Warszawa, Poland
[b] Department of Geological Sciences, University of Oregon, Eugene, OR 97302, USA

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ABSTRACT

The Eifelian Zachełmie succession consists of several transgressive–regressive cycles, 1 to 3 m thick, starting with evenly laminated marly–shaly dolomicrites and transitioning upward into irregularly laminated dolomitic laminites with well-preserved sedimentary textures. Their upper levels are frequently mud-cracked, and they are topped by massive to nodular dolomite beds, 5 to 30 cm thick, which exhibit various degrees of internal deformation. These disturbed beds were investigated in detail on the basis of saw-cut slabs, thin sections, SEM, mineralogical XRD and chemical analyses including stable oxygen and carbon isotopes. The investigations revealed a range of paleosol features, such as columnar peds, characteristically deformed surfaces (microbial earth), tubular structures interpreted as plant roots, and blackened clasts. The SEM images show that the beds are finely detrital in nature; the dolomitic silt is interpreted as having been reworked from adjacent laminated microbial muds. This interpretation is confirmed by the consistent marine stable isotope signatures of the dolomite. Slight depletion in ^{13}C points to a minor authigenic addition related to soil CO_2 input and/or microbial activity.

The disturbed beds are interpreted as waterlogged paleosols showing different stages of pedogenesis related to varying durations of subaerial exposure, most likely ranging from hundreds to a few thousands of years. The paleosols developed on low-relief coastal deflation plains separating shallow lagoons fed by marine waters. The semi-arid to sub-humid seasonal climate is indicated by evaporite traces, the development of columnar peds, and the covariance of the C and O stable isotopic values.

The Zachełmie disturbed beds appear to represent a unique example of dolomitic paleosols retaining the nearly marine chemical signatures of their marine-lagoonal dolomitic substrates, with little meteoric or vadose-evaporitic overprint. Their occurrence in the Zachełmie succession significantly changes our views on early tetrapod habitats, which apparently included permanently elevated and sparsely vegetated areas adjacent to shallow marine lagoons.

1. Introduction

The Eifelian (early Middle Devonian) dolomitic strata of the Zachełmie Quarry section in southern Poland became widely known owing to the discovery of the earliest tetrapod tracks ever documented in the fossil record (Niedźwiedzki et al., 2010). Earlier stratigraphical and sedimentological observations of the section outlined a general paleogeographical-facies interpretation of an extensive shallow-water shelf with restricted dolomitic sedimentation (Narkiewicz and Narkiewicz, 2010). Subsequently, more detailed sedimentological and petrological studies revealed the presence of cycles within the Zachełmie marginal marine succession. The topmost, regressive segments of the cycles include highly internally disturbed beds, marking prolonged periods of subaerial exposure. The beds appear to represent a rare example of paleopedological processes developing on dolomitic substrates, and they seem to be influenced in part by plant growth.

Dolomitic paleosols, although less common in the stratigraphic record than calcareous paleosols (Wright, 2007; Sheldon and Tabor, 2009), are nevertheless widely described in the literature, mainly in continental fluvial or lacustrine successions (e.g., Spötl and Wright, 1992; Colson and Cojan, 1996; Williams and Krause, 1998; Schmid et al., 2006; Khalaf, 2007; Alonso-Zarza and Wright, 2010b). Only a few known examples are related to marginal marine environments, and these are interpreted either as brackish marshes (e.g., Wright, 1994; Wright et al., 1997) or proximal carbonate platforms or ramps under semi-arid to arid climatic conditions (Elrick and Read, 1991; Balog et al., 1997; Haas, 2004). The described Polish paleosols are unique, as they punctuate a marine-lagoonal dolomitic succession that is essentially devoid of coals or evaporites. In this respect, the Zachełmie examples appear to augment the inventory of Early to Middle Devonian paleosols related to land plant expansion, which previously have been described primarily from clastic alluvial facies (e.g., Driese and Mora, 1993; Retallack, 1997; Retallack et al., 2009; Mintz et al., 2010).

Previous interpretations of the earliest tetrapod habitats assumed either largely aquatic lagoonal-peritidal environments (Niedźwiedzki

* Corresponding author.
E-mail address: marek.narkiewicz@pgi.gov.pl (M. Narkiewicz).

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et al., 2010) or coastal woodlands (Retallack, 2011a). The results of this study introduce a considerable modification to these earlier views, as they indicate the presence of emergent, sparsely vegetated areas adjacent to shallow-water lagoons. This has a direct bearing on a long-standing evolutionary problem, namely, the paleoecological context for the development of quadrupedality (presence of four legs) and terrestriality among vertebrates.

2. Stratigraphic and paleogeographic setting

The Zachełmie Quarry section (50.96924°N 20.68366°E) is located in the northwestern Holy Cross Mountains in central Poland (Fig. 1). During the Eifelian, this area was a part of a belt of shelf basins on the southern rim of the Old Red Continent (Laurussia), at mid to low paleolatitudes. Zachełmie was located near the southern margin of the subordinate Łysogóry-Radom Basin. This depocenter was characterized by open marine deposition, in contrast to the very shallow, marine, restricted Małopolska carbonate platform in the south and the shallow marine, evaporitic to continental carbonate-terrigenous facies of the Lublin Basin in the east and north (Narkiewicz et al., 2011).

The lower part of the Zachełmie Quarry succession comprises marly dolomitic mudstones to wackestones and dolomitic shales attributed to the Wojciechowice Formation and recently dated as mid-Eifelian (Narkiewicz and Narkiewicz, 2010). The main studied section includes two subsections, labeled EL and EM, located in the eastern part of the quarry and separated by inaccessible strata 1–2 m thick (Fig. 2). The equivalent of the lower part of the EM subsection (labeled WE) was measured 300 m to the west, along the southern quarry wall.

The investigated strata may be further subdivided into Lower and Upper Complexes. The Upper Complex is composed mainly of bioturbated dolomitic mudstones to wackestones with remains of crinoids, ostracods, conodonts, scolecodonts, and rare bryozoans. The fossils are evidence of marine subtidal sedimentation, with few ferruginized exposure surfaces near the base. The Lower Complex (up to bed EM 65), in contrast, is mainly dolomitic shales and marly dolomites organized in several shallowing upward cycles, with no open marine fossils. Characteristic features include crinkly and planar lamination, numerous desiccation structures and exposure surfaces. Three distinct track-bearing levels were found in a ten-meter-thick interval in the lower and upper part of the Lower Complex (Fig. 2).

3. Methods

The Zachełmie Quarry section was measured and sampled during 2010–2011. Field descriptions were supplemented by observations of saw-cut slabs and stained thin sections examined in transmitted light.

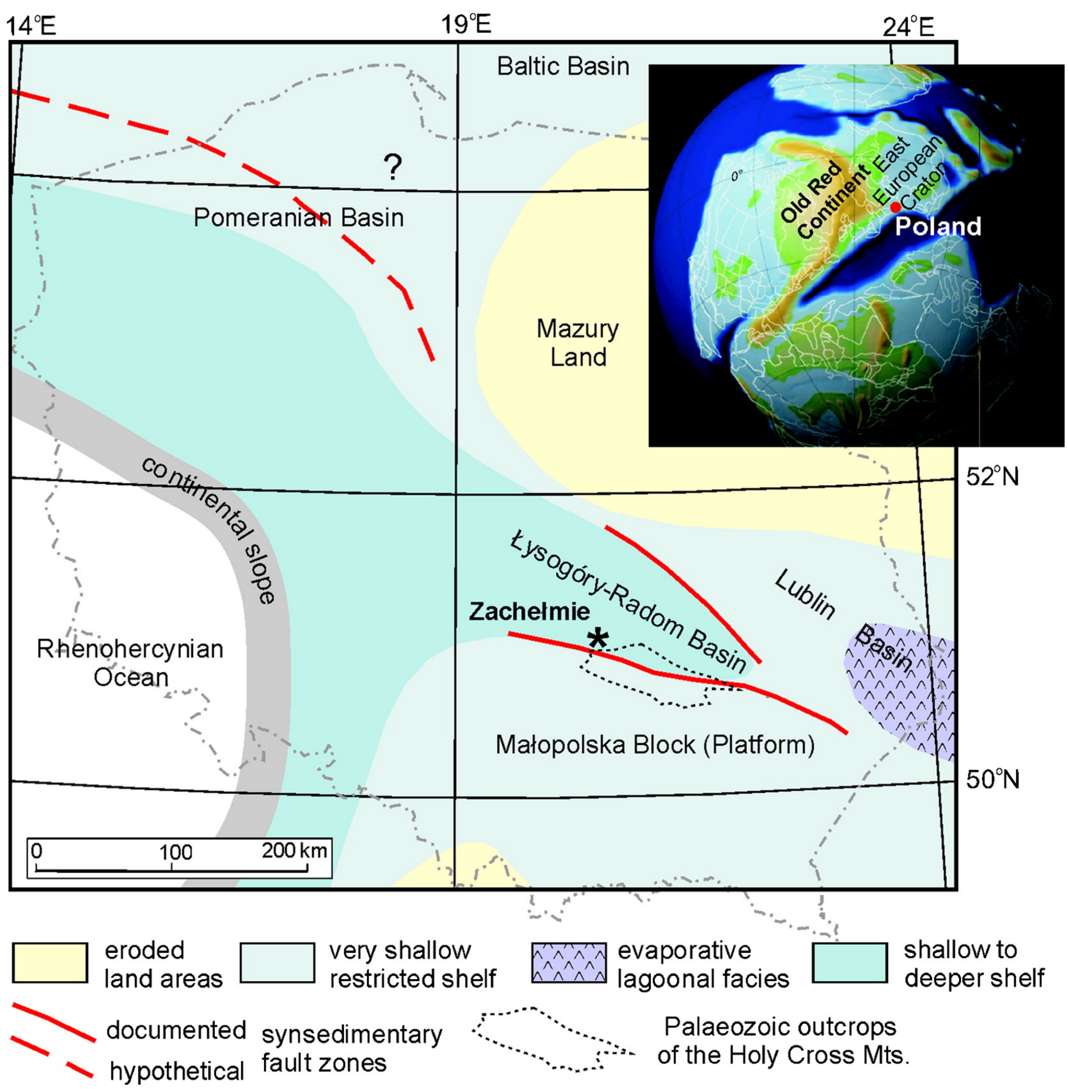

Fig. 1. Location of the Zachełmie Quarry section set against the mid-Eifelian paleogeography of Poland, shown in present-day geographical coordinates. The inset map shows Middle Devonian global paleogeography (after Scotese, 2002, PALEOMAP Project).

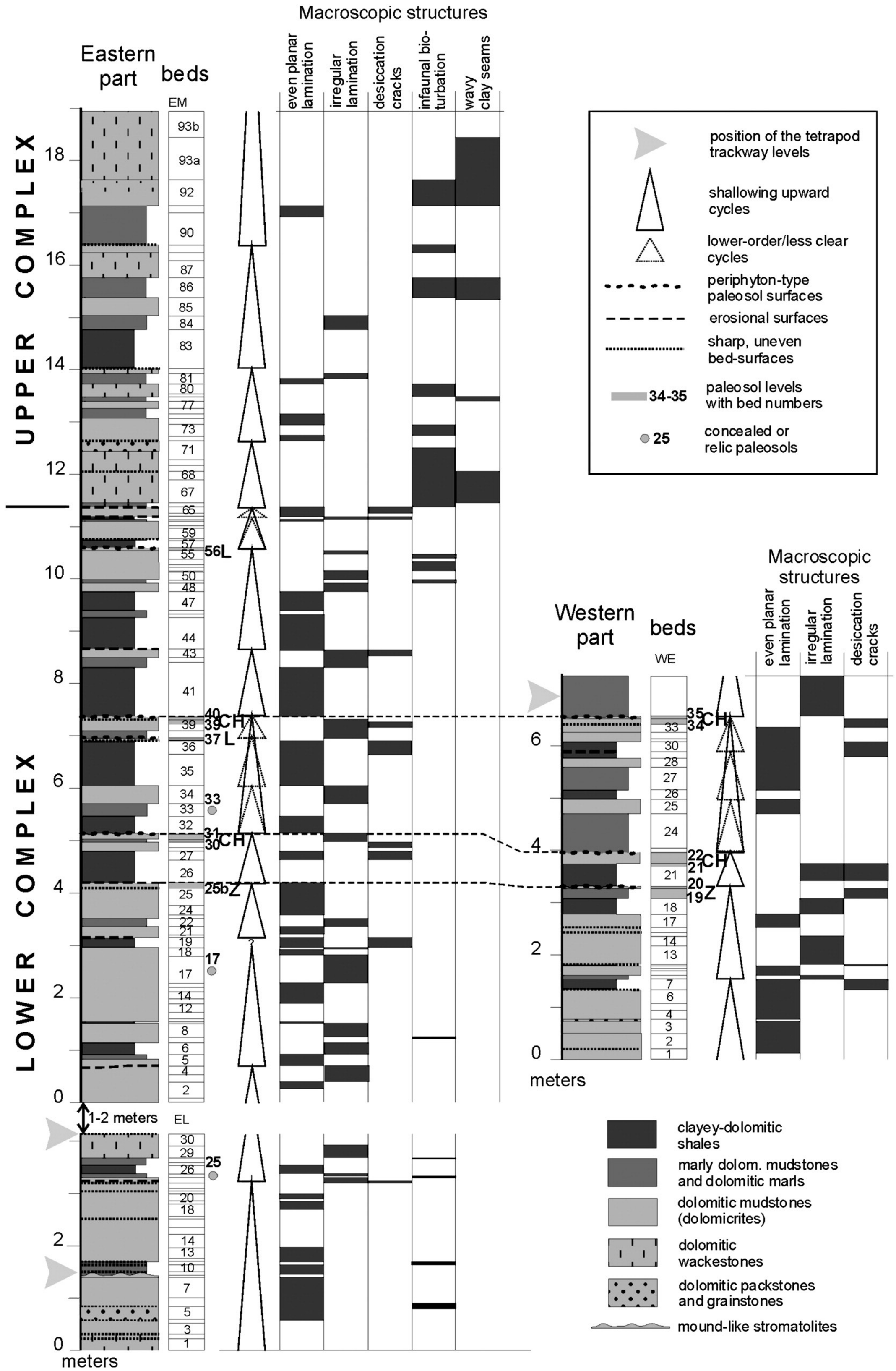

Fig. 2. Lithology, macroscopic structures, shallowing upward cycles, and distribution of the studied paleosol levels in the Zachełmie Quarry section. Abbreviations for disturbed bed types (pedotypes): L — Type 1 (Lekomin), Z — Type 2 (Zagnańsk), CH — Type 3 (Chrusty).

Powder X-ray diffractometric (XRD) analyses of nine selected samples were performed to constrain bulk mineral composition. Scanning electron microscopy was performed on several fresh rock surfaces etched for a few seconds in 1 molar HCl. Semi-quantitative elemental energy-dispersive X-ray spectroscopy (EDS) analyses were performed for selected points to determine the mineral compositions of specific grains.

A few samples from the most promising dark shaly lithologies were also analyzed for total organic carbon content (TOC; Silesian University). TOC was calculated as the difference between total carbon and total inorganic carbon using an Eltra CS-500 IR-analyzer with a TIC module. The isotopic analyses of carbon and oxygen in dolomite were performed in the Institute of Geological Sciences (Polish Academy of Sciences) in Warsaw. Our $\delta^{13}C$ and $\delta^{18}O$ data are given relative to the V-PDB standard. For the oxygen data, the fractionation correction for dolomite was applied according to Rosenbaum and Sheppard (1986). Major elements were analyzed using X-ray fluorescence (XRF; Philips PW 2400 spectrometer); trace and rare earth element (REE) components were determined by inductively coupled plasma mass spectrometry (ICP-MS; ELAN DRC II, Perkin Elmer).

4. Results

4.1. Depositional cyclicity

The shallowing upward cycles generally begin with dolomitic shales and marls displaying thin, regular bedding and predominantly planar lamination, with rare small-scale cross-laminated sets (Figs. 3, 4B). The evenly laminated beds grade upward into dolomites exhibiting irregular lamination, fenestral structures and continuous and brittle small-scale internal deformation (Fig. 4C, D). Minor intraformational erosional surfaces may truncate the laminae, sometimes with associated small clasts (Fig. 4A).

In the upper segments of the cycles, lamination is commonly disrupted by desiccation cracks (Figs. 2, 3). The heavily disturbed levels are separated by a gradational boundary from the underlying mud-cracked laminites. They form massive marly dolomitic beds with variable quartz sand and silt components, 5 to 30 cm (but mostly between 15 and 20 cm) thick. In outcrop, these beds can be identified easily by their pale yellowish to pinkish color and sharp planar to (more often) uneven upper bedding planes. The upper bedding planes exhibit a fibrous texture and undulating microrelief on exposed bedding surfaces. Further consideration will focus on the description and interpretation of these layers, referred to below as the "disturbed beds."

4.2. Macro- and microscopic characteristics

Close inspection of polished slabs and thin sections reveals varying degrees of disruption and fragmentation of laminae in the disturbed beds (Fig. 5A, C), leading to the formation of fitted and intraformational breccias and conglomerates. Black clasts of sub-centimeter size ("black pebbles"; Strasser, 1984) are common (Fig. 5B). Internal erosion surfaces and dissolution structures are also present (Fig. 5D). The processes associated with these destructional features may eventually lead to the development of a largely homogenized rock showing only relics of original structures such as lamination.

Another characteristic feature of these beds is the presence of irregular root-like tubular structures (Fig. 5B). They usually have small diameters (up to a few millimeters) and in most cases are preserved as subvertical, brownish seams, interpreted as relics of root organic matter. In some cases, these structures form networks with associated small-scale dissolution structures (Fig. 5D). Some have drab (greenish gray, Munsell 10GY6/1) haloes extending outward from the dark trace into the red and brown matrix; less commonly, other structures dissipate downward into numerous finer filaments.

Macroscopic plant remains and phytoclasts are rare and poorly preserved in the studied succession. They were found mainly in loose debris, making it difficult to relate them to specific beds. Generally low organic content was confirmed by low TOC values in three of the darkest gray shales selected for analysis from the Lower Complex (0.09, 0.9, and 0.16% TOC in beds EL 8, EL 26, and EM 57, respectively).

The features described above are evident in varying degrees within the disturbed beds, reflecting variable intensities of internal reworking.

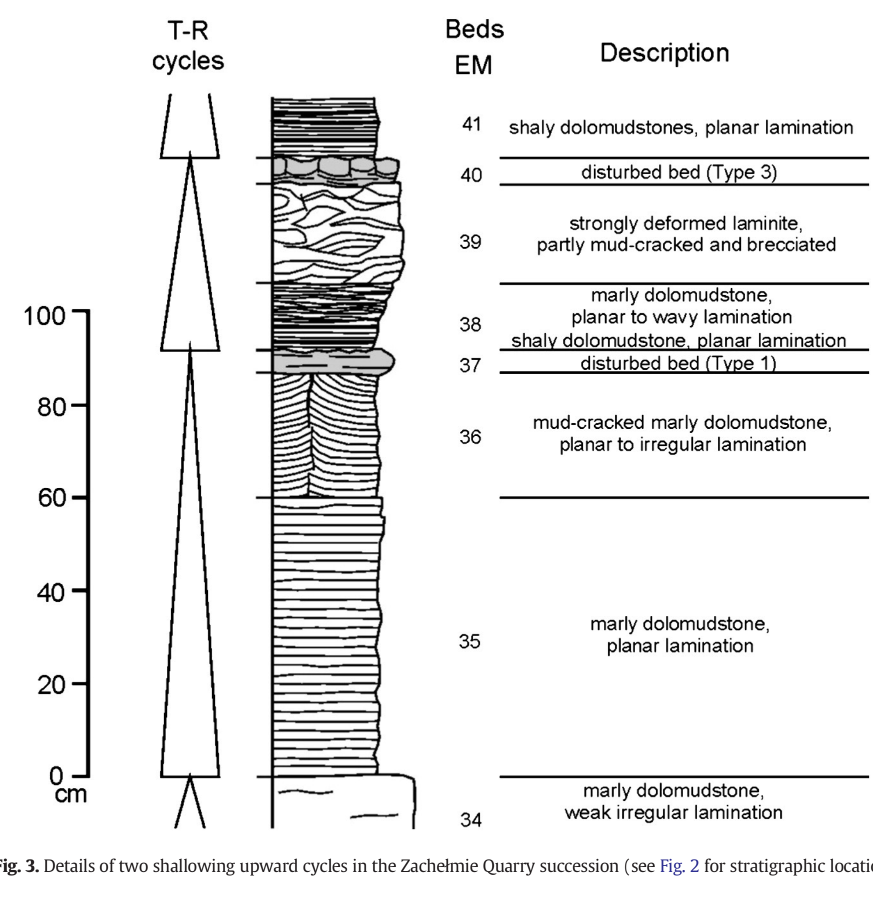

Fig. 3. Details of two shallowing upward cycles in the Zachełmie Quarry succession (see Fig. 2 for stratigraphic location).

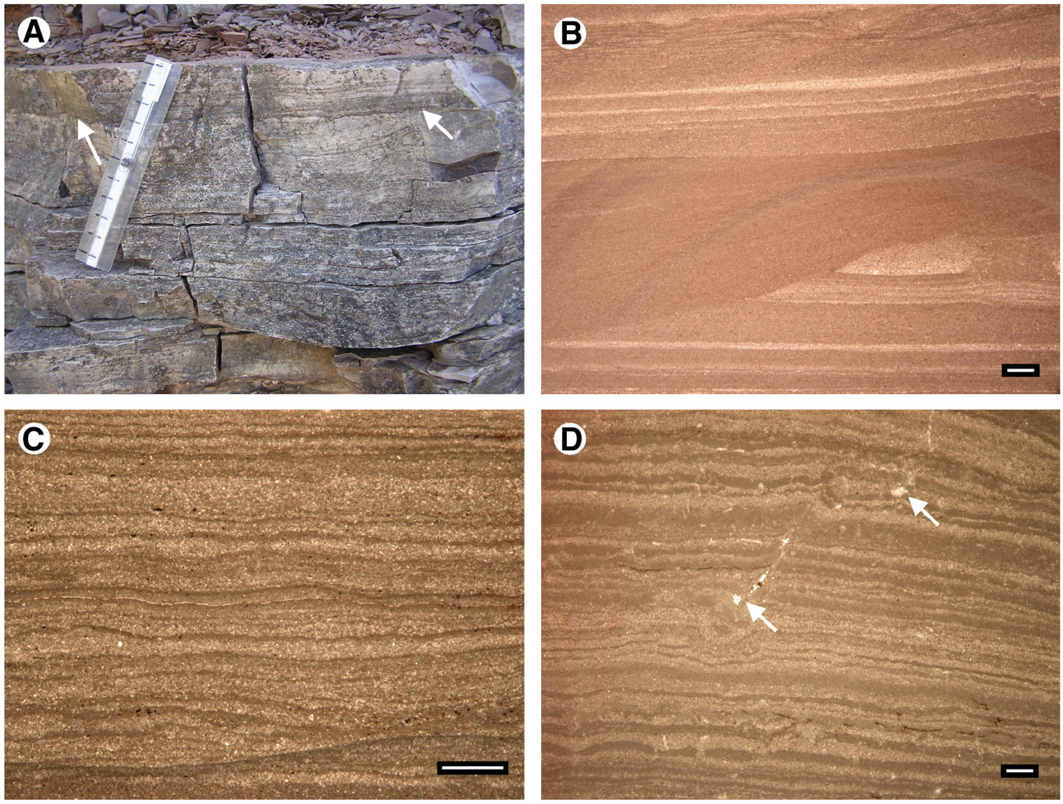

Fig. 4. Characteristic sedimentological features of the Zachełmie dolomites. A: field photo (ruler is ca. 12 cm long); B–D: stained thin sections (scale bars = 1 mm). A. Irregularly laminated dolomite mudstones in bed WE 43, with a flat erosional surface (arrowed) truncating upturned laminae in the underlying mud-cracked level. B. Planar laminite with a minor erosional surface. C–D. Irregular laminites in beds WE 7 (C) and EM 20 (D); note fenestral structures in D (arrowed).

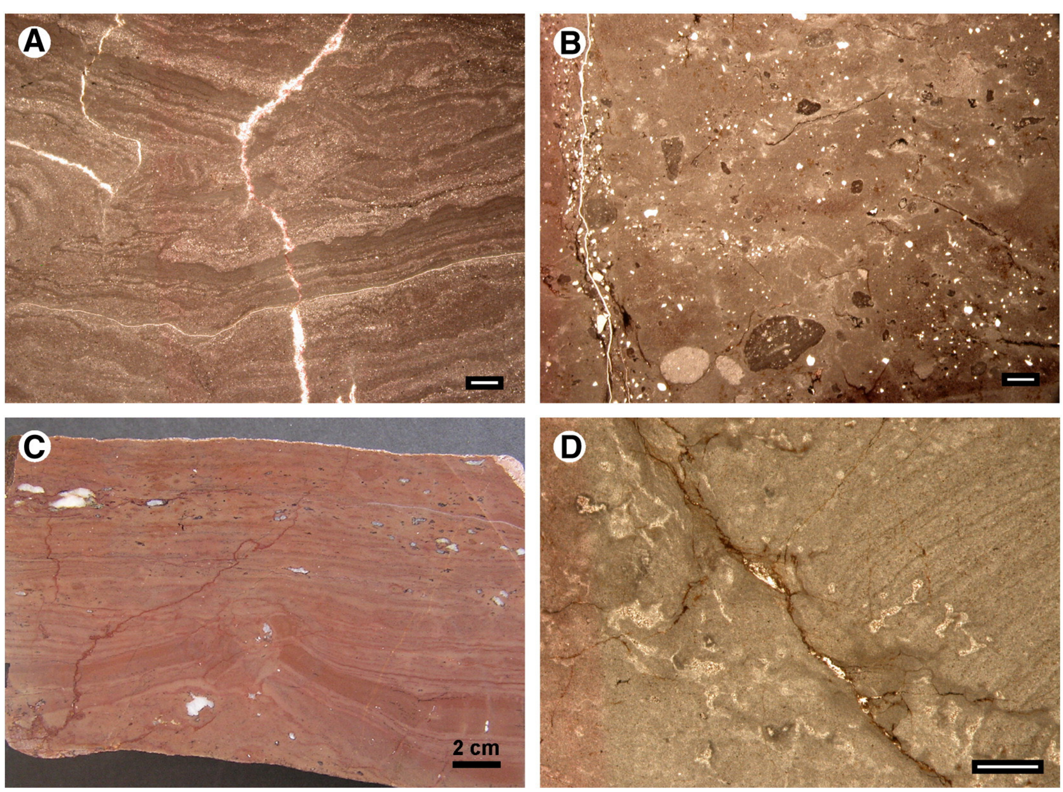

Fig. 5. Characteristic sedimentological features of the Zachełmie dolomites. A, B and D: stained thin sections (scale bars = 1 mm); C: hand specimen. A. Deformed irregular lamination in bed WE 35. B. Intraclastic wackestone in bed EM 33, with small black pebbles and a vertical root-like structure (left). C. Irregular laminite with evaporite pseudomorphs (white) and a mud-cracked level at the base (bed WE 3). D. Irregular dissolution vugs infilled with sparry dolomitic cement, associated with an oblique plant root structure (bed EM 25).

Three general categories can be distinguished (Types 1 to 3). Beds EM 37 and EM 57 are thin (less than 10 cm thick), light to medium gray, homogeneous to slightly wavy-bedded dolomitic mudstone to wackestone (Type 1; Fig. 6A). In thin sections, they display irregular lamination, which is disturbed but still recognizable, and a few thin root-like structures (Fig. 6B). In the intermediate category (Type 2; beds WE 19–20), well-bedded, flaggy dolomitic mudstone to wackestone ca. 30 cm thick is disrupted by Fe-stained nodules and columnar peds (Fig. 7A, B). The peds are separated by vertical fissures filled with clay minerals, ca. 50 cm deep after correction for compaction. The apparent plant roots are large and more common than in Type 1 (Fig. 7C).

Two distinct levels correlatable between the eastern and western parts of the quarry were attributed to the most advanced stage of internal reworking (Type 3). The beds are characterized by thicknesses of 15–20 cm, medium gray to pinkish colors, and a homogeneous to nodular structure sometimes displaying an irregular columnar pattern (Fig. 8A–C). The irregular upper bedding planes exhibit a characteristic pattern illustrated in Fig. 8D. Root-like structures are common (Fig. 9A–C), and black pebbles are frequently observed in thin sections. In addition, there are three other levels, likely representing similar development, marked with gray circles in Fig. 2. They are not obvious in the field, however, and may be erosional relics best observed in thin sections (Fig. 5B).

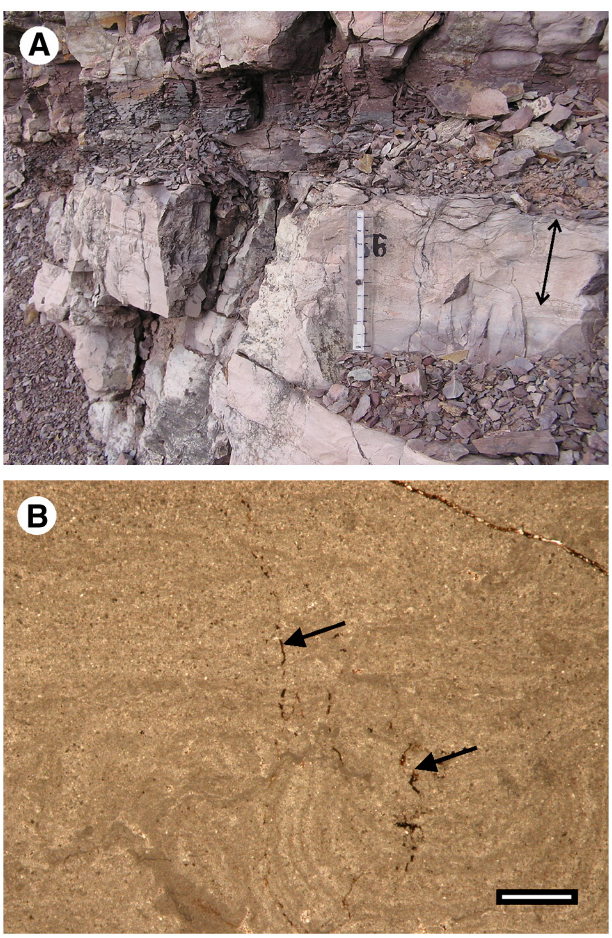

Fig. 6. Type 1 disturbed bed (EM 56). A. Disturbed level (arrowed) with slightly wavy bedding and a sharp boundary with overlying clayey-dolomitic shales at the base of a shallowing upward cycle (ruler is ca. 12 cm long). B. Thin section showing disturbed lamination and a few thin vertical root-like tubules (arrowed) of possible fungal origin (scale bar = 1 mm).

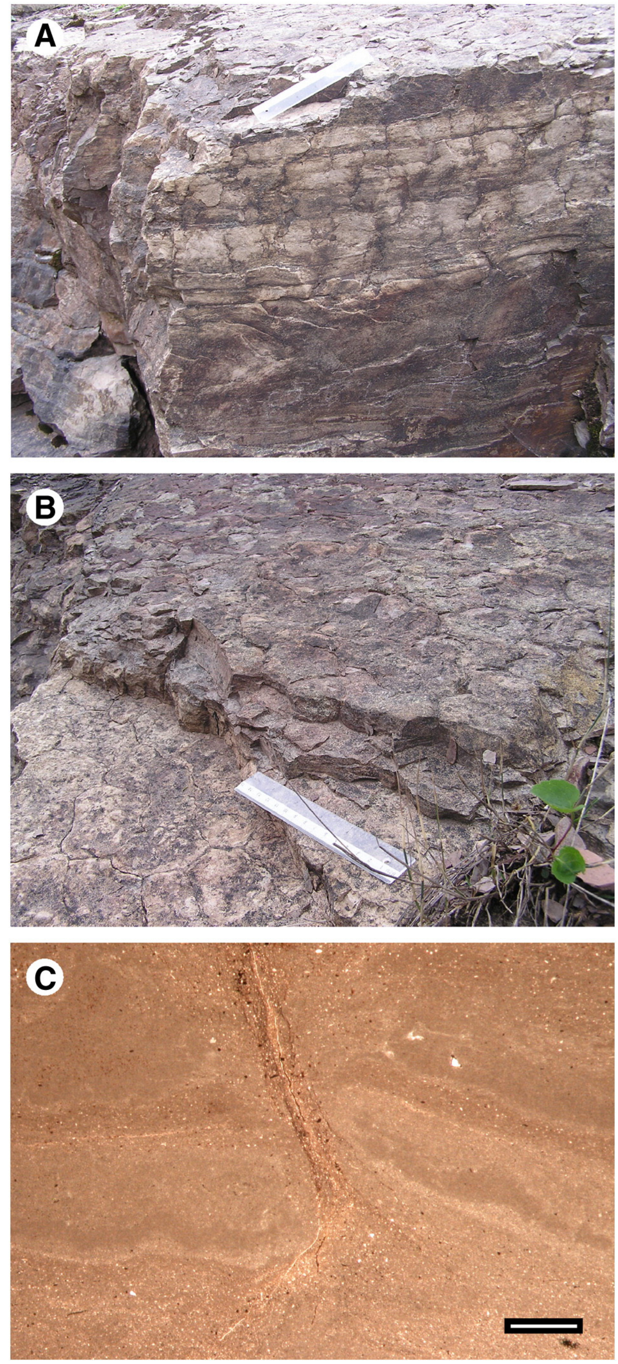

Fig. 7. Type 2 disturbed beds. A. Irregular columnar peds in beds WE 19–20 (ruler is ca. 12 cm long). B. Top surfaces of columnar peds on the upper plane of bed WE 19 and cracked microbial earth texture on the upper plane of bed WE 20 (ruler is ca. 12 cm long). C. Thin section of a laminated dolomicrite disrupted by a root-like tubule in the upper horizon of bed WE 19 (scale bar = 1 mm).

4.3. Mineralogy and elemental chemistry

Stained thin sections show that minerals in the disturbed beds (and also in the enclosing strata in general) almost exclusively include micritic dolomite, quartz, and muscovite. Calcite occurs only locally as a post-tectonic vein-filling blocky cement and a late dedolomite related to Permian–Triassic or recent weathering processes. XRD analyses confirmed the presence of dolomite as the principal carbonate mineral, as well as a variable admixture of clay minerals dominated by illite with less abundant chlorite. Dispersed Fe-oxide mineralization is ubiquitous, commonly imparting a red color and Liesegang banding. The lower part

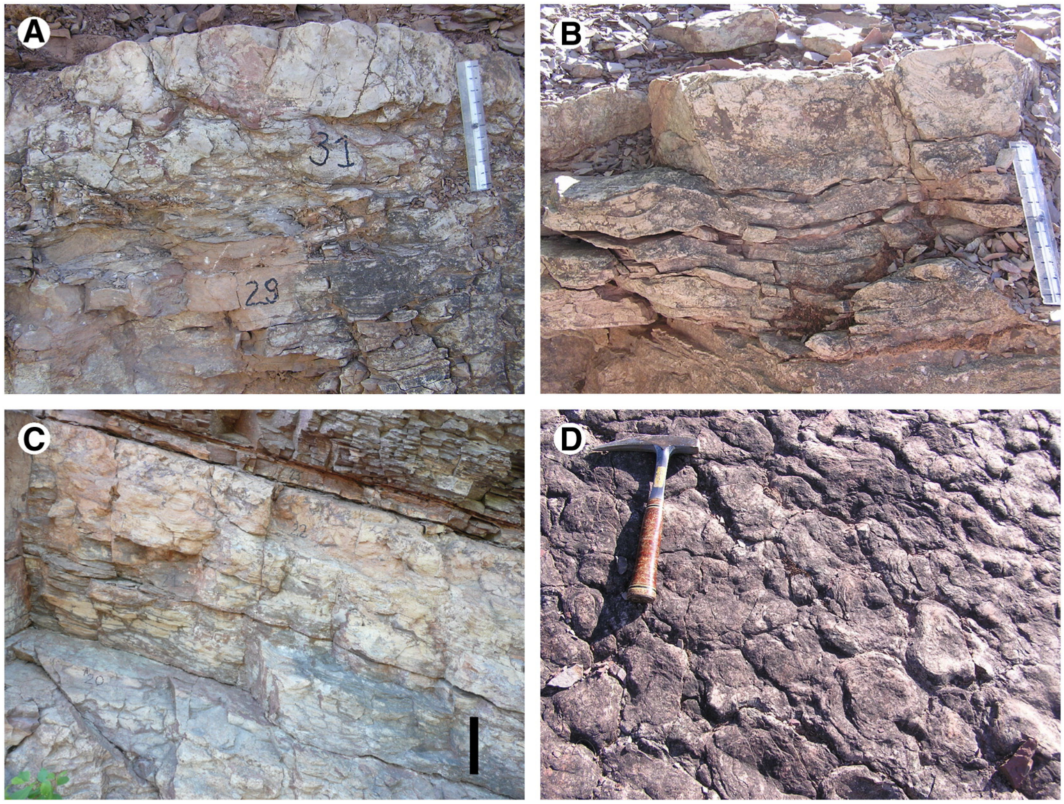

Fig. 8. Type 3 disturbed beds (field photos). A. Columnar dolomitic bed EM 31, with a sharply defined upper surface and a gradational base transitioning into marly dolomitic mudstones with irregular lamination and desiccation structures (ruler is ca. 12 cm long). B. Massive bed EM 40 overlying laminated deposits with desiccation cracks (note upturned edges of desiccation polygons; ruler is ca. 12 cm long). C. Pinkish nodular bed WE 22 overlying mud-cracked laminite and underlying thin, planar beds of marly dolomitic mudstone, which constitute a transgressive portion of a successive shallowing upward cycle (scale bar = 15 cm). D. Cracked microbial earth on the upper plane of bed WE 35. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

of the Lower Complex (subsections EL and lower EM) contains traces of vanished evaporites. They are represented by millimeter-sized casts of anhydrite crystals and nodules up to 2 cm long, which are filled with quartz and saddle dolomite (Fig. 5C). In addition, rare compacted casts of halite cubes are present in dolomitic marly shales.

Elemental whole-rock chemistry of the disturbed beds is based on a limited number of analyses (9 samples). These samples have generally high values of CaO (averaging 20.42 wt.%) and MgO (14.79 wt.%) consistent with high amounts of dolomite. Nevertheless, they are typically enriched in terrigenous components—mainly Al_2O_3, SiO_2, TiO_2 and K_2O—relative to the average for the entire section (based on a total of thirty samples analyzed during this study). Additionally, enrichment in Fe_2O_3 is associated with a terrigenous clay admixture: there is a strong positive correlation between Al_2O_3 and Fe_2O_3 (correlation coefficient $r = 0.96$). This correlation may be indirect, owing less to Fe content in clays (e.g., chlorite) than to secondary Fe-oxide impregnations in more marly beds.

The disturbed beds are also enriched in trace elements such as V, Cr, Co, Ni, Rb, Cs, Ba and U, which are strongly correlated with Al_2O_3 ($r > 0.85$). Furthermore, they are enriched in Zn, Mo, and Pb, which are fairly well correlated with alumina (r between 0.6 and 0.8). No enrichment is observed in the case of Cu and Sr, which are moderately well correlated with the carbonate content. All analyzed REEs are also enriched relative to the section mean, although they are depleted when compared with modern Queensland muds (Fig. 10; Kamber et al., 2005). Some of the REEs (Sc, La, Ce, Pr, and Th) may be correlated with clay mineral content (correlation with Al_2O_3, $r > 0.8$).

4.4. SEM characteristics

SEM studies demonstrate that the disturbed beds and enclosing sediments consist primarily of dolomite grains and crystals ranging from 1 to 10 μm (Fig. 11A–C). In addition, quartz and layered aluminosilicates (clay minerals, sericite, muscovite) were also detected. Some dolomite crystals are euhedral, but most are subhedral and/or broken to some extent, pointing to the detrital nature of the dolomicrite (Fig. 11B). Irregular, spherical or oval grains with diameters less than 10 μm constitute an important component of the dolomitic sediments (Fig. 11A, C). They may be homogeneous or exhibit a complex structure of interlocking submicron-size crystallites. In many examples, the grains are less regular in shape, but they nevertheless show a suggestion of circular outlines and internal complexity. These spherical grains are best developed in the disturbed beds (Fig. 11C), but they are also associated with irregular laminites (Fig. 11A) and with other microfacies varieties. The dolomite in the disturbed beds is characterized by the widest size range and most chaotic arrangement of constituent grains and crystals.

4.5. Stable carbon and oxygen isotopes

To characterize isotopic composition, we considered data from 13 samples collected from different levels within the disturbed beds (Table 1; Fig. 12). The pool included 4 samples from bed WE 34 (B–E, in order of increasing depth) and 3 samples from beds WE 18–19 (Z-2, Z-4, and Z-6 located 2, 14, and 30 cm below the top of WE 19, respectively). The mean $\delta^{18}O$ for the samples (−2.60‰) corresponds to the mean value for the entire Lower Complex (−2.56‰; $n = 52$), whereas $\delta^{13}C$ has a more negative average value (−1.1‰ vs. −0.5%). This $\delta^{13}C$ signature is more negative than that of the irregular laminites, which have an average value of −0.24‰ ($n = 13$).

Another characteristic of the isotopic signatures is the covariance of $\delta^{13}C$ and $\delta^{18}O$ (Fig. 11; $r = 0.72$), which contrasts with the lack of any significant correlation among all 88 samples from Zachełmie ($r = 0.28$). The correlation becomes even stronger ($r = 0.78$) after

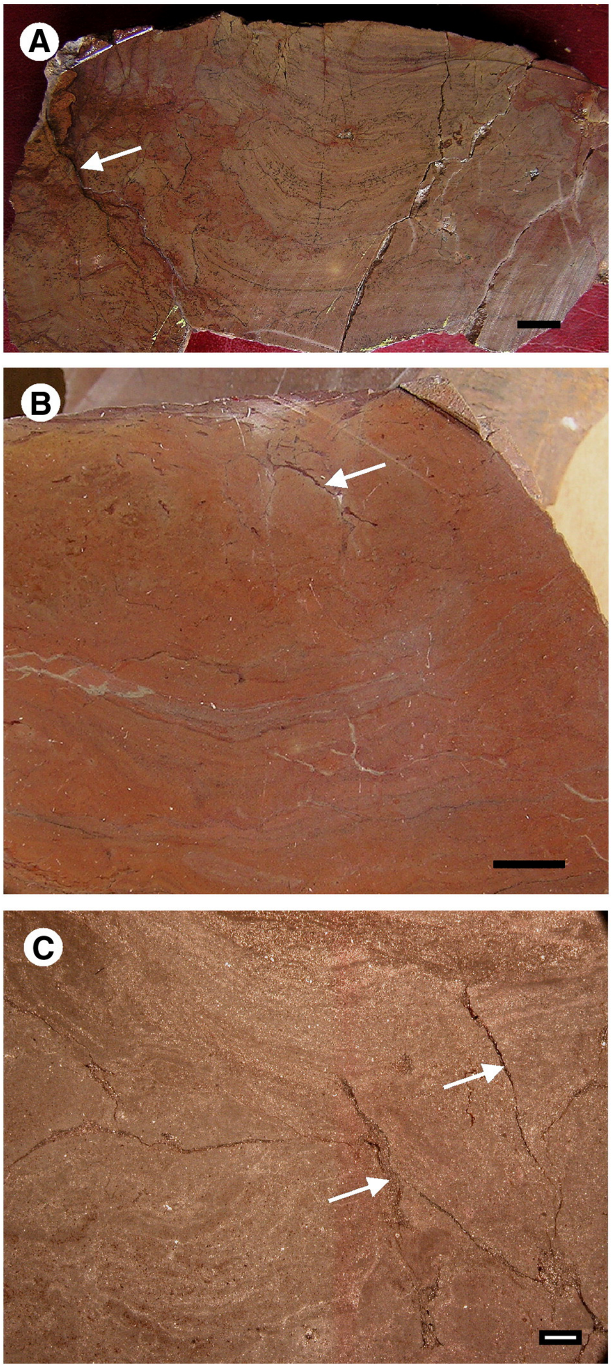

Fig. 9. Type 3 disturbed beds. A–B: saw-cut hand specimens; C: thin section (scale bar = 1 cm). A. Upper part of bed EM 31, showing disruption of surficial cumulic laminite (center) by root-like tubules (top left, arrowed). B. Topmost part of bed EM 40, with disrupted irregular lamination (bottom) grading upward into homogenized sediment with small root-like tubules (dark, arrowed). C. Bed EM 40, showing small root-like tubules disrupting irregular laminite; darker clayey silt (upper right) is sediment overlying the disturbed bed.

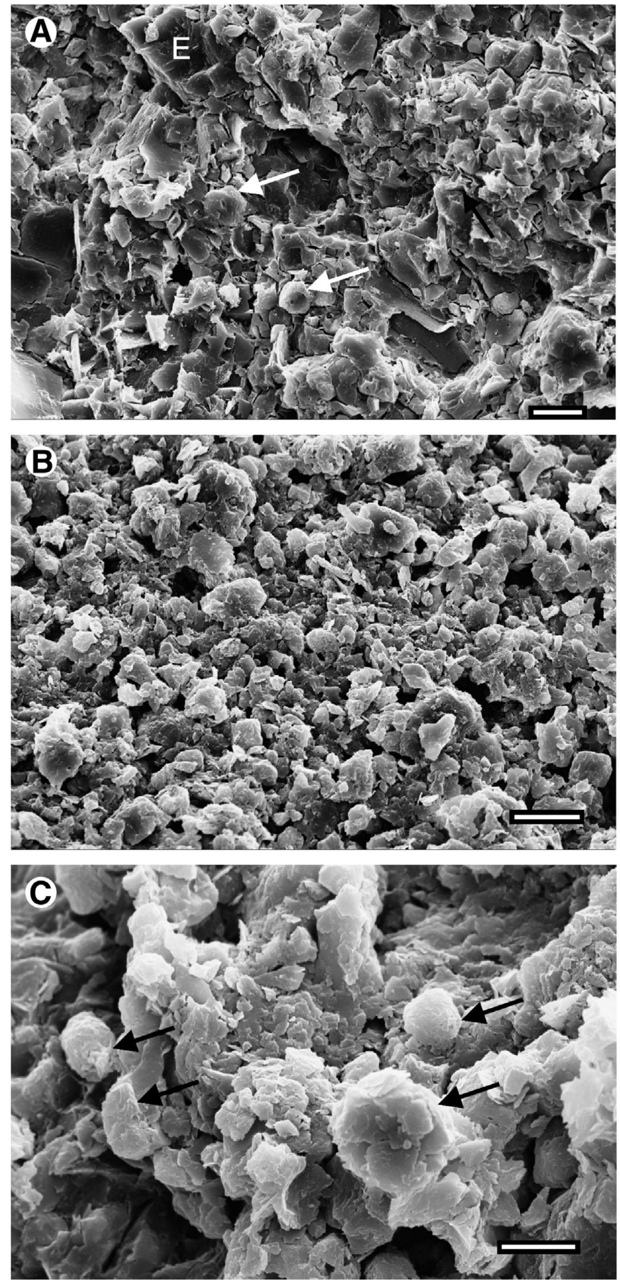

Fig. 10. SEM photographs of freshly broken, slightly HCl-etched rock surfaces. A. Irregularly laminated dolomicrite (bed EM 20) with globular structures of probable microbial origin (arrowed) in a partly recrystallized fine-grained dolomite (note euhedral dolomite crystal, labeled E). Scale bar is 10 μm. B–C: bed WE 20. B. Detrital appearance of dolomicrite in a Type 2 disturbed bed. Scale bar is 10 μm. C. Dolomite microspheres of presumably microbial origin (arrowed), the largest of which is composed of smaller crystallites. Scale bar is 5 μm.

the exclusion of sample EM 17, which represents an eroded surface and is likely contaminated by the irregular laminite (cf. Fig. 11). The few data points for bed WE 34 are distributed linearly within a narrow range of strongly negative $\delta^{13}C$ values and $\delta^{18}O$ values that generally decrease with depth (Fig. 11). On the other hand, the data for beds WE 18–19 (less disturbed) do not display such a depth-related trend; rather, they group around relatively high values both for carbon (ca. −0.4‰) and oxygen (ca. −2‰).

5. Interpretation

5.1. Depositional setting of the Lower Complex

Irregularly laminated muds, which occur in the middle and upper segments of the shallowing upward cycles, are composed of alternating micritic and microsparitic fine-grained laminae less than a millimeter thick (Figs. 4C–D, 5A). The sediments exhibit irregular fenestrae and wrinkled lamination surfaces in some places. Overall, the textures are similar to well-documented examples of stromatolitic microbial dolomites (e.g., Perri and Tucker, 2007; You et al., 2013). Perfect

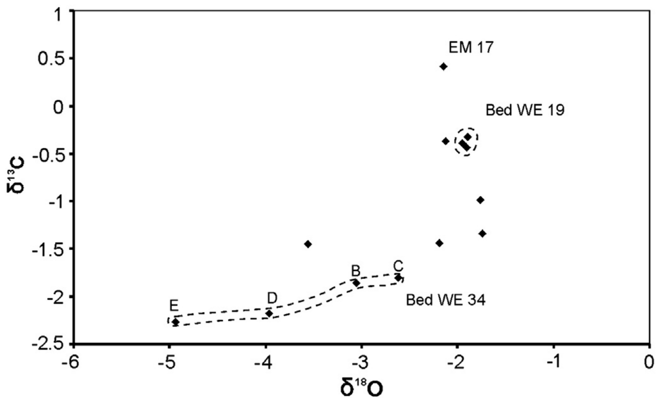

Fig. 11. Plot of $\delta^{13}C$ versus $\delta^{18}O$ values (relative to the V-PDB standard) for Zachełmie paleosol dolomites (see Table 1 for numerical values). Samples B–E (in order of increasing depth) were collected from bed WE 34.

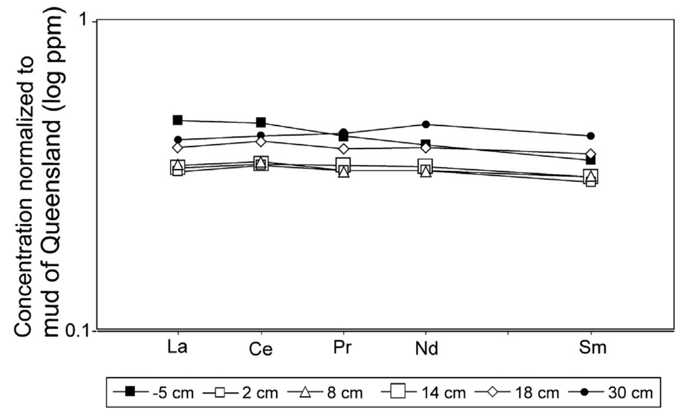

Fig. 12. REE chemical analyses (PAAS-normalized) of the Zagnańsk pedotype. Legend shows sample depths in beds WE 20 (first value) and WE 19 (subsequent 5 values).

preservation of depositional features in dolomite suggests an early, synsedimentary origin. This interpretation is supported by the C and O isotope data, which point to the marine origin of dolomitizing fluids. In particular, the oxygen isotopic composition is consistent with precipitation from Middle Devonian seawater at temperatures ranging from 25 to 45 °C (van Geldern et al., 2006; Narkiewicz, 2009).

A model for microbial dolomite formation was proposed by Vasconcelos and McKenzie (1997) on the basis of present-day laminated dolomitic muds forming in the Brazilian coastal lagoon Lagoa Vermelha. The lagoon is a few meters deep and is fed by marine waters from the Atlantic Ocean. Dolomitic deposition takes place under seasonally evaporative conditions associated with the subtropical climate. Dolomite precipitation is mediated by microbes and occurs in extracellular substance produced by bacteria.

The microbial origin of the irregular laminites from the Zachełmie section is indicated indirectly by well-preserved stromatolitic fabrics. Although well-preserved microbial structures such as microspheres and filaments (e.g., Pruss and Payne, 2009; Spadafora et al., 2010) are not evident, there are suggestions of micron-sized globular structures preserved in partly recrystallized sediment (Fig. 11A). Other analogs with the Lagoa Vermelha sediments include early lithification phenomena and a paucity of evaporitic minerals (Sánchez-Román et al., 2009; Spadafora et al., 2010).

The high carbon isotopic signatures apparently contradict an organic origin for the dolomite. Nevertheless, Wacey et al. (2007) demonstrated that dolomite of microbial origin may have relatively high $\delta^{13}C$ values, reflecting a considerable contribution of inorganic carbon (e.g., from marine waters). This suggests that the Zachełmie dolomitic lagoon was fed by marine waters, which implies a connection with the open sea, possibly via narrow straits and/or shallow subsurface flow. The mud-cracked irregular laminites in the uppermost parts of the cycles testify to shallowing and the gradual restriction of a lagoonal environment, culminating in isolation from the marine influence, desiccation and subaerial exposure.

Table 1
Stable carbon and oxygen isotope data from the Zachełmie paleosols.
Abbreviations for dolomitic microfacies: BC — breccia/conglomerate; Lm — irregular laminite; (d) — deformed; Lm-L — mixed irregular and planar laminite; M — mudstone; Ws — skeletal wackestone. See Fig. 2 for location of beds/samples.

Bed/sample	Microfacies	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
EL 25	M/BC	−2.127	−0.370
EM 17	Lm/BC	−2.141	0.416
EM 31	BC/Lm	−1.765	−0.992
EM 33	BC	−1.736	−1.344
EM 37	Lm(d)	−2.192	−1.442
EM 56	Lm(d)	−3.555	−1.454
WE 34B	Lm(d)	−3.052	−1.856
WE 34C	Lm(d)	−2.617	−1.803
WE 34D	Lm-L	−3.961	−2.180
WE 34E	Lm-L	−4.937	−2.268
WE 19-Z2	Lm(d)	−1.905	−0.439
WE 19-Z4	Ws	−1.891	−0.327
WE 18-Z6	M	−1.953	−0.393
Mean values		−2.602	−1.112

Evenly laminated dolomitic shales and mudstones in the lower segments of the sedimentary cycles do not show any evidence of the fabrics described above. Planar lamination, occasionally with small-scale cross-laminated sets, and a general absence of open marine fauna indicate restricted lagoonal conditions with prevailing current-controlled fine-sediment dispersion and deposition. The nearest clastic source areas are flat and distant (cf. Fig. 1), suggesting that the terrigenous admixture is aeolian in origin. Very low TOC levels and poor preservation of both palynomorphs and macrophytes point to well-oxygenated conditions. This—along with the presence of evaporite traces—indicates that environmental stress excluding macro- and microfauna was related to salinity fluctuations, rather than to low oxygen levels.

The formation of dolomite in the lower segments of the Zachełmie cycles cannot be attributed directly to microbial activity, as the sediments lack clear stromatolitic textures. Nevertheless, there are frequent examples of alternating irregular and planar laminites, particularly in the central segments of the shallowing-upward cycles. Moreover, dolomite spheroids of probable bacterial origin were also observed in the planar laminites. This indicates that dolomite particles in the evenly laminated dolomicrites may in fact represent reworked microbial dolomite that was transported by currents, waves or winds from a nearby lagoonal setting undergoing temporary erosion. This conclusion is consistent with the similarity of C and O isotopic compositions in irregular (microbial) and planar (abiotic) laminites.

5.2. Origin of disturbed beds: role of pedogenesis

The association of the disturbed beds with the topmost, mud-cracked parts of the shallowing upward cycles clearly points to emergence episodes as the source of the characteristic fabrics observed. Reworking of microbial laminites may be attributed partly to alternating desiccation–wetting processes (e.g., Alonso-Zarza and Wright, 2010b) as well as to subaerial mechanical erosion and redeposition observed in the presence of local intraclasts. The intraclasts include blackened clasts that are commonly interpreted as evidence of lengthy subaerial exposure and associated pedogenic processes (Strasser, 1984, 1988; Vera and Jiménez de Cisneros, 1993; Lang and Tucci, 1997). Episodic growth of evaporitic minerals alternating with carbonate dissolution during more humid periods could also have contributed to internal deformation of the sediment.

We believe, however, that the above phenomena cannot fully explain the extent of reworking, particularly in the most intensely disturbed beds, and that vegetation development was an important factor. Although plant remains are present only rarely in the beds, there is ubiquitous evidence of structures attributable to plant root development. These are invariably preserved as traces, in which the original organic tissue is lost due to decay processes in generally well-aerated environments. Moreover, poor preservation of these structures may be related to poor initial development, reflecting the early stages of vascular plant root evolution (Brasier, 2011). On the other hand, the structures dissipating downward into numerous finer filaments may be attributed to giant fungi comparable to *Prototaxites* (Hueber, 2001) or *Mosellophyton* (Schaarschmidt, 1974). Similar root-like structures were noted in Siluro-Devonian paleosols by Driese and Mora (2001) and Hillier et al. (2008). The presence of root structures supports the idea that the high degree of internal deformation in the beds is partly due to bioturbation by plants, which is a key factor in reworking of paleosol material (e.g., Wright, 1994).

Three distinct types of paleosols can be recognized in the Zachełmie Quarry (Fig. 13; Table 2), equivalent to the three types of disturbed beds described above. These pedotypes are described here in order of increasing degree of pedogenesis, reflecting progressive alteration of the dolomitic substrate. Relic bedding is most persistent in the *Lekomin pedotype* (Type 1), the surfaces of which are nearly flat with some small-scale relief. This pedotype represents a degree of development characteristic of Fluvisols (Food and Agriculture Organization, 1974) or Entisols (Soil Survey Staff, 2010). Eye-catching columnar peds in the *Zagnańsk pedotype* (Type 2) are not sodic and thus do not constitute a natric horizon in a Solonetz; rather, they represent deep cracking in a Calcic Cambisol (Food and Agriculture Organization, 1974) or Inceptisol (Soil Survey Staff, 2010). This pedotype has strongly cracked yet fibrous-wrinkled surfaces. The *Chrusty pedotype* (Type 3) has the most poorly preserved bedding and contains possible evaporite pseudomorphs, similar to Cambisols (Food and Agriculture Organization, 1974) and Inceptisols (Soil Survey Staff, 2010). Its cracked and wrinkled surfaces are also overfolded and deformed (Fig. 8D), suggesting that they rose well above the surface when hydrated.

We also sampled the disturbed bed WE 19 in more detail to investigate the possibility of vertical chemical variability. The various molar weathering indices show a relatively uniform vertical distribution of chemical compositions (Fig. 13). This indicates a poorly developed soil profile and further confirms an incipient stage of paleosol development.

In all three of the pedotypes, gray colors are dominant, supporting the identification of the paleosols as Hydrosols (Isbell, 1996) and Gleysols (Food and Agriculture Organization, 1974). Each of the recognized pedotypes has distinctive microbially induced sedimentary structures representing conditions ranging from waterlogged to desiccated. These textures are comparable to periphyton algal mats, which are known especially well from the Florida Everglades (Gaiser et al., 2006; Thomas et al., 2006). Periphyton is the largely cyanobacterial coating that grows around plants submerged in water for part of the year. On mangrove trunks and prop roots, periphyton mats are heavily disrupted and hang in skeins, but they are little disrupted by sawgrass marshes (Retallack, 2012). The Lekomin pedotype surface textures resemble periphyton in very sparsely vegetated environments, whereas the Zagnańsk surfaces resemble periphyton in modern sawgrass meadows, and Chrusty surfaces include deformed skeins similar to periphyton hanging from mangroves.

Drab-haloed root traces observed in the Zagnańsk and Chrusty pedotypes are very common in Phanerozoic paleosols and are thought to form by microbial gleization of the soil matrix soon after burial (Retallack, 2011b). This type of coloration in paleosols is evidence that they were more or less waterlogged for most of the year, and also that they formed in topographically flat environments with shallow water tables (Vepraskas and Sprecher, 1997). Waterlogged non-peaty and non-saline soils are best known from coastal deflation plains in which loose dry silt has been wind-scoured almost down to the water table, where grains cannot be lifted by wind (Rhodes, 1982; Peterson et al., 2007). Coastal deflation plains are by definition close to the water table but vary slightly in elevation due to the presence of sand drifts and the margins of coastal lakes, lagoons and tidal creeks (Fig. 14). The Chrusty pedotype (characterized by pink coloration and evaporitic pseudomorphs) developed at a higher elevation than the Zagnańsk

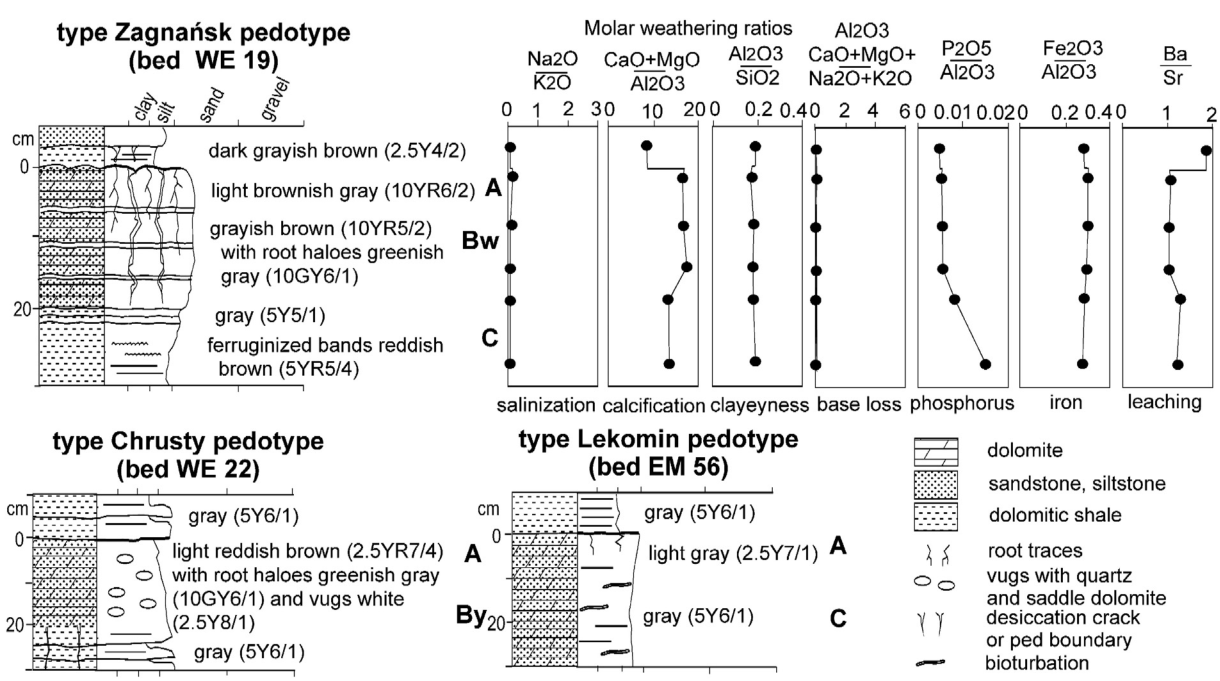

Fig. 13. Types of Zachełmie paleosols, including the chemical composition of the Zagnańsk pedotype.

Table 2
Classification and interpretation of Zachełmie paleosols.

Pedotype	Lekomin	Zagnańsk	Chrusty
Diagnosis	Thin microbially laminated and domed dolomitic gray surface (A) horizon with fine root-like tubules over laminated dolomitic mudstone or shale (C)	Microbially laminated and cracked surface (A horizon) over columnar dolomitic reddish gray (10R5/1) (Bw) horizon	Massive reddish gray (10R5/1) dolomitic surface (A) horizon over light reddish brown (2.5YR7/4) dolomite (By) with scattered pseudomorphs after evaporites
U.S. taxonomy (Soil Survey Staff, 2010)	Fluvent	Endoaquept	Aquisalid
Food and Agriculture Organization (1974)	Calcaric Fluvisol	Calcaric Gleysol	Gleyic Solonchak
Australian Classification (Isbell, 1996)	Lutic Rudosol	Epicalcareous Supratidal Hydrosol	Gypsic Supratidal Hydrosol
Former organisms	Periphyton and small land plants	Coastal shrubland of early land plants	Microbial earths and small land plants
Palaeoclimate	Not diagnostic	Sub-humid sub-tropical	Not diagnostic
Palaeotopography	Lagoon margin flats	Lunettes (clay pellet dunes)	Lagoon margin
Parent material	Dolomitic loess	Dolomitic loess	Dolomitic loess
Time for formation	10–100 years	1000–2000 years	1000–2000 years

pedotype (characterized by persistent relic bedding), although the more clayey Zagnańsk pedotype cracked more deeply during the dry season than the more silty Chrusty pedotype. The Lekomin pedotype formed closer to a standing body of water such as a perennial lake or very shallow lagoon.

Different types of vegetation can be theorized for each of the pedotypes on the basis of the size of root-like traces, ranging from small (axes less than 5 mm in diameter) herbaceous plants scattered across the Lekomin pedotype to low stands of herbaceous plants (axes 5–10 mm) in the Zagnańsk pedotype and small shrubby plants (axes 10–12 mm) in the Chrusty pedotype. Based on the drab color and high carbonate content of the paleosols (Retallack, 1992), these were alkaline wetland environments, generally comparable to early succession fen, well-developed fen, and shrub-carr communities of the present day. Present-day fen vegetation includes grasses and sedges; shrub-carr vegetation is largely willow and alder (Haslam, 2003). Rare remains of large plants found in the Zachełmie Quarry that may be plausibly associated with the Chrusty pedotype are comparable to *Mosellophyton* and *Huvenia* (Hass and Remy, 1991). Smaller plants associated with the Lekomin and Zagnańsk pedotypes may have included herbaceous rhyniophytes and zosterophylls known from other Devonian wetland paleosols of comparable age (Driese and Mora, 2001).

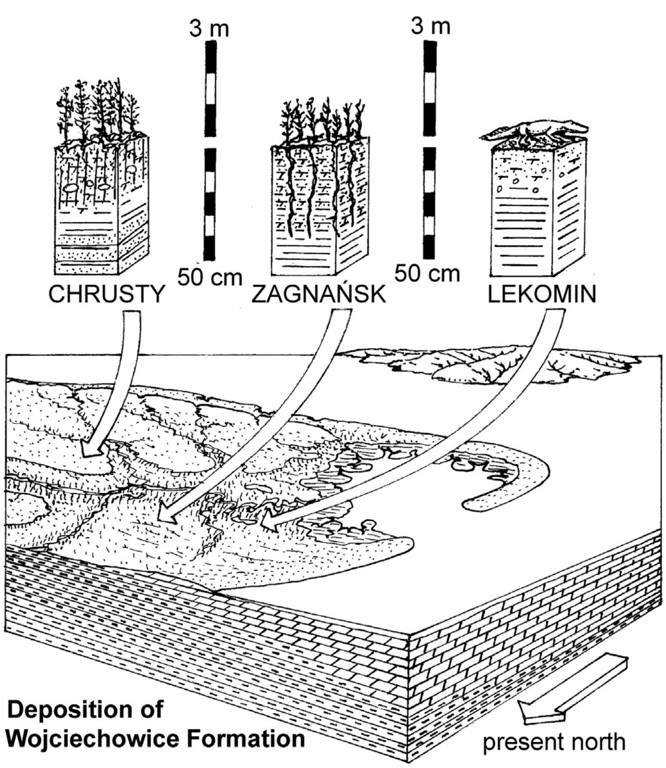

Fig. 14. Conjectural reconstruction of Middle Devonian (mid-Eifelian) paleosols and their relationship to sedimentary environments, as interpreted for the Zachełmie Quarry succession. Vegetation is based on fragmentary trimerophytes.

6. Discussion

6.1. Isotopic composition and parent materials

The isotopic signature of dolomite in the paleosols (Table 1) is very similar to that of both the irregular (microbial) and planar (finely detrital) laminites, which are interpreted as having formed under the influence of marine fluids. In particular, the carbon isotopic ratios are only slightly lighter than the marine Eifelian values (van Geldern et al., 2006). These results seem to contradict the paleosol origin of the disturbed beds, as they differ considerably from the reported range of O and C isotopic signatures for dolomite paleosols. Values for oxygen and carbon isotopes in paleosol carbonates are generally more negative, related to meteoric and organic influences on soil CO_2 composition, respectively (e.g., Spötl and Wright, 1992; Wright et al., 1997; Williams and Krause, 1998; Kearsey et al., 2012), or may be enriched in ^{18}O as a result of evaporation (e.g., Kohut et al., 1995).

One possible reason for this discrepancy may be that the paleosol dolomite is predominantly detrital in origin. Based on SEM observations (Fig. 11B), the particles seem to be mostly reworked in situ from the underlying lagoonal muds and/or transported by wind from exposed parts of the lagoon. Another reason may be the inhibition of pedogenesis by waterlogging in coastal deflation plains during part of the year. Thus, the contribution of authigenic dolomite in the paleosols appears to be negligible, although lighter $\delta^{13}C$ values relative to other facies nevertheless may indicate some input from soil CO_2 (Retallack, 2012). Furthermore, observations of a few relatively well-preserved globular structures (Fig. 8C) may indicate a bacterial contribution to authigenic dolomite formation in the paleosols. Moreover, the possibility cannot be excluded that precipitation of dolomicrite may have been promoted through a symbiotic relationship between fungi and plant roots (Sanz-Montero and Rodríguez-Aranda, 2012).

The positive correlation between C and O stable isotopic signatures, although based on a limited number of samples, appears to be significant. It seems to be consistent with evaporative modification of carbonate-precipitating fluids in a vadose system (Ufnar et al., 2008). A similar positive linear covariance was observed in modern caliches in the western US (e.g., Knauth et al., 2003) and in Upper Permian pedogenic dolomite in the Southern Urals (Kearsey et al. (2012). Nevertheless, of the two paleosols sampled for vertical variability (beds WE 19 and WE 34), only the more advanced Chrusty pedotype (WE 34) suggests a decreasing-downward trend (Fig. 11). This trend may reflect increasing evaporation (Ufnar et al., 2008) and the influence of isotopically heavy atmospheric CO_2 (Driese and Mora, 1993) in the upper paleosol levels.

Partial inheritance of marine isotopic compositions has also been documented in modern Texas Vertisols containing reworked marine shells, but even in these examples, the pedogenic micritic carbonate is isotopically distinct from marine carbonate (Michel et al., 2013). The stronger marine signal in the Zachełmie paleosols may be related to their weak development. Modern soils of the San Joaquin Valley in California, which have comparable degrees of bedding disruption and formed under broadly similar climatic conditions to those inferred for Zachełmie (Table 2), include very weakly developed soils of the 200-year-old post-Modesto III surface and weakly developed soils of the 3000-year-old post-Modesto II surface (Harden, 1982). These short periods of soil formation represent upper temporal limits for the formation of the described Devonian paleosols (Table 2) because Devonian plants did not mix soil as effectively as modern plants (Retallack and Huang, 2011).

6.2. Climate

Paleosols of the Zachełmie Quarry are too weakly developed to be good indicators of paleoclimate, partly because they were incipient and partly because they were associated with high water tables. Furthermore, the high carbonate content in the paleosols precludes the use of established geochemical climofunctions based on non-carbonate soil components (Sheldon and Tabor, 2009). The paleosols of the Zachełmie Quarry are thus azonal, in the sense that they do not clearly reflect a particular climate, type of vegetation, or soil map unit from the Food and Agriculture Organization's (1974) world map. On the other hand, the paleosols do not show evidence of extreme climates: they exhibit no deformation resembling sand wedges associated with frigid paleosols, nor do they contain kaolinite or gibbsite (see Section 4.3) indicative of humid tropical conditions (Retallack, 2001).

The Chrusty pedotype may include evaporite relics, but these do not contain the sand crystal or typical nodularized form of pedogenic gypsum associated with aridland soils (Retallack and Huang, 2010). The distribution of evaporite relics throughout a profile with gray coloration suggests that these salts formed in playa-type soils comparable to Solonchaks under marked dry season conditions (Food and Agriculture Organization, 1974). Additional evidence of a dry season is provided by the correlation between $\delta^{13}C$ and $\delta^{18}O$ (Fig. 11; see above), which may be related to paleoevaporation. Deep cracking of the Zagnańsk pedotype suggests wetland water table movements of approximately half a meter, which also constitutes evidence of a marked dry season. According to De Vleeschouwer et al. (2012), the mid-Devonian climate in the western-central European area of the Old Red Continent margin was monsoonal, with a prevailing wind from the southeast during summer and from the northeast during winter. If that was the case, the dry season could have occurred during winter.

6.3. Comparisons with similar pedogenic dolomites

Although primary dolomite is common in many calcretes (Wright and Tucker, 1991), dolomitic paleosols or dolocretes are much less common than those composed of low-magnesian calcite (Wright, 2007; Sheldon and Tabor, 2009). Moreover, many of the reported examples are attributed to groundwater processes in continental settings (e.g., Spötl and Wright, 1992; Colson and Cojan, 1996; Williams and Krause, 1998; Schmid et al., 2006; Khalaf, 2007; Alonso-Zarza and Wright, 2010b).

Paleosols described in Poland seem to fall under another broad category of pedogenic or vadose dolomites (e.g., Spötl and Wright, 1992; Calvo et al., 1995) typified by a spectrum of organic and/or vadose structures including plant roots, pisoids, meniscus cements, etc. They are described mostly in fluvial clastic deposits such as redbeds (nodular dolomicrite; e.g., Spötl and Wright, 1992; Williams and Krause, 1998; Kearsey et al., 2012; VanDeVelde et al., 2013) and thus are clearly irrelevant to the paleosols studied here. Fe-dolomicritic paleosols attributed to mixed seawater–freshwater dolomite precipitation in brackish coastal marshes (reviewed by Wright, 1994; see also Muchez and Viaene, 1987; Searl, 1988; Wright et al., 1997) also do not compare closely to the Zachełmie examples. The closest correspondence appears to be with a few reported carbonate lacustrine or palustrine facies and coastal to marginal marine or peritidal systems, briefly reviewed below.

According to Alonso-Zarza and Wright (2010a), dolomite may form in palustrine carbonates under arid climate conditions or from chemically evolved groundwater in which less soluble phases have been removed during flow towards or within the lake. Calvo et al. (1995) described such dolocretes in the Miocene Madrid Basin, where they formed close to the lacustrine dolomitic facies and thus clearly were influenced by saline waters from the adjacent lake. Their pedogenic origin was indicated by prismatic structures, rhizoconcretions, clay cutans, and alveolar fabrics (with related roots). Armenteros et al. (1995; Tertiary, Spain) reported formation of dolocretes with scarce pedogenic features, connected with saline mud flats and lakes in an alluvial fan to ephemeral lake system under seasonally dry climate conditions. They proposed an Mg-rich groundwater origin for these dolocretes, with evaporative pumping of fluids enriched in magnesium by interstitial gypsum precipitation.

A few published reports describe dolomitic paleosols or dolocretes related to marine carbonate peritidal successions. Perhaps the best known examples are pedogenic dolomite horizons topping or underlying the Upper Triassic platform cycles (Main Dolomite or Hauptdolomit unit) in the European Alpides (e.g., Balog et al., 1997; Haas, 2004; Pomoni-Papaioannou, 2008). These paleosols include argillaceous and commonly laminated, brecciated and pisolitic dolomite horizons a few centimeters thick, overlying disconformities topping peritidal cycles and truncating dolomitic microbial stromatolites. A strong vadose diagenetic overprint including meniscus and pendant cements, teepees and vadose pisolites is typical. The paleosols are thought to have developed under semi-arid conditions in subaerially exposed tidal flats.

Similar examples from the Givetian in Alberta (Canada) are represented by intertidal massive dolostone and supratidal terrigenous shaly dolostone couplets affected by pedogenic, meteoric, and phreatic processes (Williams and Krause, 2000). However, a strong late diagenetic overprint is suggested by crystalline textures obliterating primary structures (microbial lamination, root structures) and by depleted oxygen isotopic values. Finally, Elrick and Read (1991) described Fe-stained, unfossiliferous dolomite (0.03 to 0.3 m thick) capping peritidal cycles and overlying irregular surfaces of dolomitic, mud-cracked cryptalgal laminite or breccia. These horizons developed on the broad, storm-dominated inner pericratonic ramp (Lower Carboniferous, Wyoming and Montana, USA).

In summary, dolomite paleosols developing on dolomitic substrates, i.e., by subaerial alteration of syndepositional dolomites, are rare and poorly known, particularly when compared with clastic continental systems. The Eifelian examples from the Zachełmie Quarry in Poland apparently have no direct analog among the dolomite paleosols described in published studies. They do not represent a continental lacustrine setting, as exemplified by Spanish Tertiary deposits, nor do they represent regressive peritidal cycle caps comparable to the Devonian to Triassic examples cited above. They are somewhat similar to the latter, however, in that they developed over microbially laminated, partly mud-cracked, early diagenetic (syndepositional) dolomites. In addition to originating in a different paleogeographic setting, the lagoonal Zachełmie cycles do not display evidence of the intense vadose zone processes that are particularly characteristic of the Upper Triassic examples (Balog et al., 1997; Haas, 2004; Pomoni-Papaioannou, 2008). On the other hand, root traces indicate that they were influenced by the development of vegetation. The contrasting characteristics of the Zachełmie paleosols may be explained by more humid, seasonal climatic conditions in the Polish basin.

7. Conclusions

The lower, tetrapod track-bearing part of the Eifelian Zachełmie section comprises dolomitic lagoonal shallowing upward cycles capped by mud-cracked microbial laminites. These are overlain by disturbed beds related to prolonged subaerial exposure. The disturbed beds represent waterlogged paleosols ranging from the most incipient Lekomin pedotype (containing well-preserved relics of microbial lamination) through the intermediate Zagnańsk pedotype (typified by columnar peds) to the most advanced Chrusty pedotype (characterized by intense reworking, common plant roots and characteristically textured, cracked and wrinkled upper surfaces). The associated vegetation is interpreted as scattered herbaceous early land plants, fen containing herbaceous early land plants with periphyton, and shrub-carr with thick and deformed periphyton, respectively.

The general setting of paleosol development most likely consisted of low-relief coastal deflation plains adjacent to lagoonal areas with strong marine connections and predominantly microbial dolomite sedimentation. The parent material in the paleosols is composed mostly of reworked lagoonal dolomitic silt particles characterized by marine isotopic signatures, with some addition of isotopically lighter dolomite related to the input of soil CO_2 and/or organic carbon. In view of the available sedimentological evidence, the climate may be interpreted as semi-arid to sub-humid with monsoonal seasonality. In particular, a pronounced dry season is indicated by traces of evaporites, fluctuating groundwater levels (evidenced by the development of columnar peds), and covariance of oxygen and carbon isotope values.

The generally limited advancement of pedogenic processes may be explained primarily by short durations of exposure, on the order of a few thousand years in the case of the best developed Zagnańsk and Chrusty pedotypes. Nevertheless, emergent, flat, sparsely vegetated areas were clearly present in the proximity of shallow-water lagoons; these adjacent environments collectively formed the habitats of early tetrapods. This finding has important implications for possible scenarios that interpret the development of quadrupedality and terrestriality among vertebrates.

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