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The Upper Triassic crenogenic limestones in Upper Silesia (southern Poland) and their paleoenvironmental context

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ABSTRACT

Upper Triassic (Norian) freshwater carbonates, up to 30 m in thick, occur in the northern part of Upper Silesian basin. These sediments, called the Woźniki Limestone, form a SE-NW–striking elongate (90 km) and narrow (<10 km) belt. The Woźniki Limestone overlies (mostly discordantly) Carnian gypsiferous red beds and underlies the uppermost Triassic–Lower Jurassic continental clastic deposits. Laterally, the carbonates are replaced by a typically red bed clastic assemblage formed under arid and semiarid climatic conditions.

Several limestone types have been recognized within the freshwater facies, including travertines, and fluvial, palustrine and pedogenic carbonates. Palustrine limestones form a major component. Common tepee structures, karst breccia, silicified horizons, and weathering breccia indicate that the palustrine carbonates have undergone subaerial exposition and pedogenic alteration. Palustrine carbonate sedimentation has been interrupted and replaced by fluvial sedimentation. The fluvial sediments mark the pluvial climate episodes that inhibited carbonate deposition.

The studied basin displays a striking scarcity of lacustrine sediments, which may be explained in terms of hydrological and climatic controls. We infer that the carbonates were deposited within shallow swampy depressions, fed by springs of deep-circulating groundwater, partly of hydrothermal nature, under dry and semidry paleoclimatic conditions in a fault-bounded basin. The travertines precipitated directly near the springs, whereas the remnant solutions formed a broad swamp area where palustrine carbonates formed. It seems very likely that the carbonate-bearing solutions were causally related to the hydrothermal karst that occurs within the Triassic and Paleozoic basement limestones.

Keywords: freshwater limestones, travertines, paleoenvironments, Upper Triassic, Poland.

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RESUMEN

La parte norte de la cuenca alta de Silesia incluye una unidad de carbonatos de agua dulce, de 30 metros de potencia y edad Triásico Superior (Noriense). Estos sedimentos, denominados Caliza Woźniki forman un cinturón estrecho y alargado (<10 km) en dirección SE-NW. La Caliza Woźniki se apoya, casi siempre discordante, sobre las capas yesíferas rojas del carniense y sobre ella se sitúan los depósitos continentales del Triásico más alto y Jurásico inferior. Lateralmente estos carbonatos pasan a las capas rojas detríticas formadas bajo condiciones climáticas áridas y semiáridas.

Las calizas están formadas por distintos tipos de facies que incluyen: facies fluviales, palustres, pedogénicas y de surgencias. Las calizas palustres son las más abundantes. Rasgos como "tepees," brechas cársticas, horizontes silicificados y brechas de alteración indican que los carbonatos palustres sufrieron exposición subaérea y pedogénesis. La sedimentación palustre carbonática quedó interrumpida por una etapa posterior de sedimentación fluvial, que indica climas más húmedos.

Los depósitos lacustres ss, que normalmente son anteriores a los palustres, son muy escasos en esta cuenca. Esto puede ser debido a los controles hidrológicos y climáticos. Así, si se tienen en cuenta las condiciones áridas y semiáridas, el hecho de que los bordes de la cuenca son fallas y la abundancia de travertinos, se puede considerar que los carbonatos se depositaron en una depresión somera y pantanosa, abastecida por surgencias de aguas freáticas profundas (en parte hidrotermales). Los travertinos se formaron por precipitación directa en las zonas cercanas a las surgencias, mientras que el resto del agua se acumuló en depresiones pantanosas amplias donde se formaron los carbonatos palustres. Parece muy probable que las soluciones ricas en carbonato tuvieran relación con el carst hidrotermal que se desarrolló en las calizas del Triásico y Paleozoico.

Palabras clave: calizas de agua dulce, travertinos, paleoambientes, Triásico Superior.

INTRODUCTION

This paper focuses on the Upper Triassic continental sediments that occur in the northern part of the Upper Silesian basin (Fig. 1) called the Woźniki Limestone. In this paper, we use the term Woźniki Limestone (WL) as an informal lithostratigraphical unit dominated by carbonates but which also includes subordinate clastic intercalations. The Woźniki Limestone includes a range of isolated carbonate bodies surrounded by carbonate-poor, variegated muddy sediments. Fossils of the Woźniki Limestone are very scarce and limited to ostracodes and calcified plant molds. These carbonates have long been recognized as continental sediments (Roemer, 1867; Michael, 1912); however, their age and exact sedimentary context are uncertain. The common consensus is that the Woźniki Limestone formed in a lacustrine environment (Gąsiorowski and Piekarska, 1976, 1986), but no convincing evidence of such an origin has been provided so far. In fact, the sediments of the Woźniki Limestone display very few features of typical lacustrine deposits. The main goal of the present paper is to reinterpret the genesis of the Woźniki Limestone by means of sedimentological and geochemical examinations.

GENERAL AND PALEOGEOGRAPHICAL SETTING

The Woźniki Limestone forms a SE-NW–striking assemblage of carbonate bodies, stretching a distance of some 90 km and occupying ~300 km^2 (Fig. 1). Its thickness reaches up to 30 m. The Woźniki Limestone is situated between the gypsiferous Upper Gipskeuper of early Norian age and the fluvial facies assemblage of the Rhaetian (Fig. 2). The lack of fossil remnants and poorly recognized facies context has long hindered more precise age determination of the Woźniki Limestone. Its age has been assumed mainly to be Rhaetian (Znosko, 1960; Grodzicka-Szymanko and Orłowska-Zwolińska, 1972; Bilan, 1976).

According to our palynological examination, the Woźniki Limestone encompasses palynomorph taxa indicative of so-called palynostratigraphic assemblage IV (*Corollina meyeriana* zone) in the zonation scheme by Orłowska-Zwolińska (1983), Fijałkowska-Mader (1999), and Heunisch (1999). Based on the palynostratigraphical and lithostratigraphical position of the Woźniki Limestone, we estimate its age to be Norian.

The studied area was situated during Norian times within the subtropical convergence zone. Dry climatic conditions dominated; however, several humid intervals have also been recognized during this time in central Europe (Reinhardt and Ricken, 2000). The pluvial intervals were affected by other climate-forming factors, such as changes in ocean-land configuration, volcanism, or supraregional tectonic-topographical changes (Simms and Ruffel, 1990; Szulc, 2007).

It is important to note that the Woźniki Limestone is closely linked to the master fault dislocation in the region (Szulc et al.,

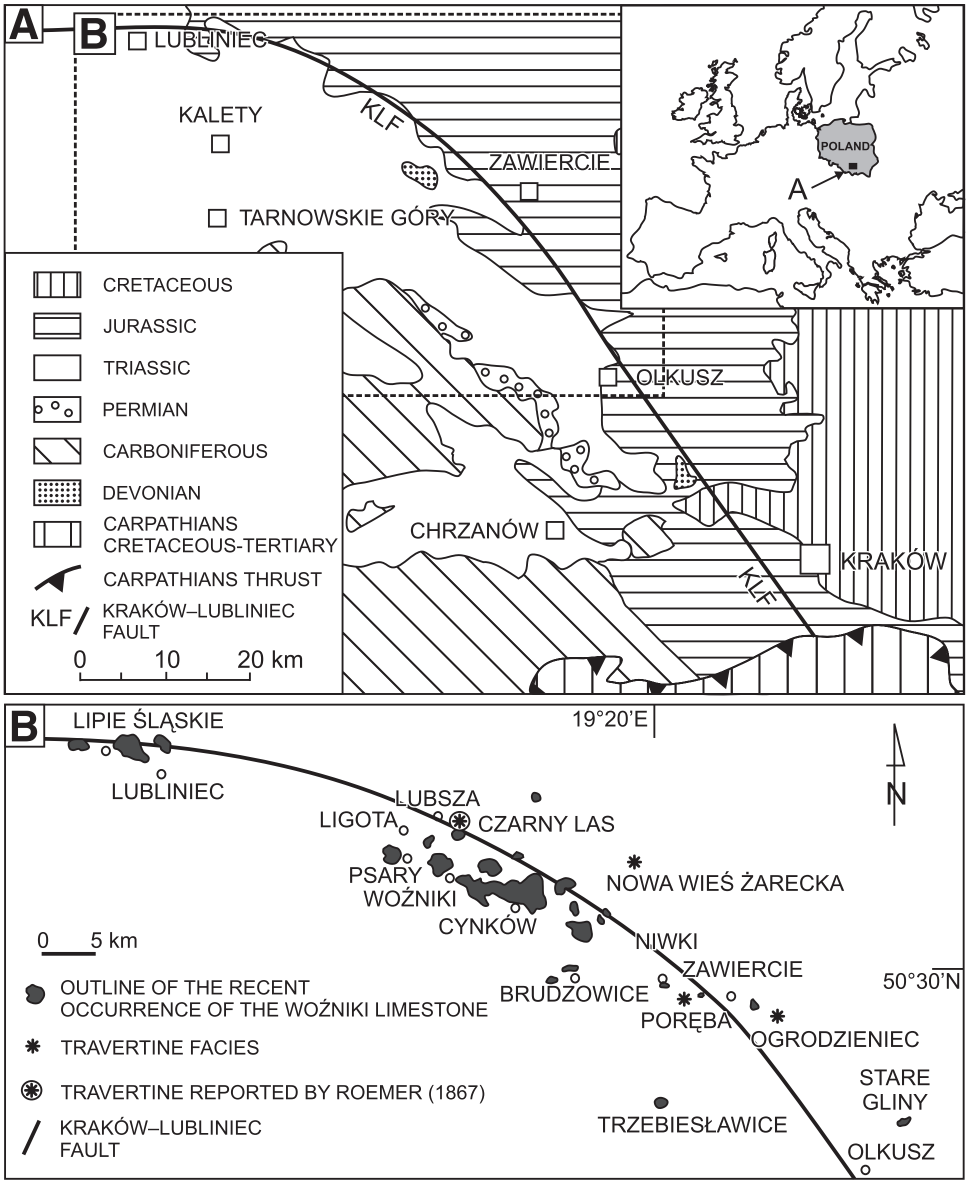

Figure 1. (A) Geological sketch map of the Woźniki Limestone, and (B) location of the studied outcrops and drill holes.

2002) (Fig. 1), called the Cracow-Lubliniec fault (cf. Morawska, 1997). Typical carbonates of the Woźniki Limestone occur in a belt of some 10 km in width, adjacent to the fault zone. Clearly, no similar facies occur outward from this belt.

The thick carbonate succession, reaching up to 30 m (Figs. 2–5), is a fundamental feature that distinguishes the Woźniki Limestone from its coeval counterparts in other regions of the mid-European Basin (see Beutler et al., 1999).

METHODS AND MATERIALS

Outcrops of the Woźniki Limestone are rare. Therefore, in order to accomplish the research goals, several holes were drilled across the entire outcrop area of the Woźniki Limestone. Twelve outcrop sections and six cores were studied for sedimentary fabrics and facies variability. The sedimentological observations were supplemented by petrological and geochemical analyses of mineralogical composition, stable isotopes, major and trace elements, and clay minerals.

The measurements of carbonate $\delta^{13}C$ and $\delta^{18}O$ were conducted with a SUMY mass spectrometer at the Institute of Geochemistry and Geophysics, the Academy of Sciences of Belarus in Minsk. The isotope ratios were measured in carbon dioxide generated by reaction of the samples with 100% orthophosphoric acid. Carbon dioxide was subsequently trapped in liquid nitrogen and purified in a vacuum. The analytical error for single measurements was ±0.2‰. Stable oxygen isotope ratios are expressed relative to Peedee belemnite (PDB) standard (see Hoefs, 1997).

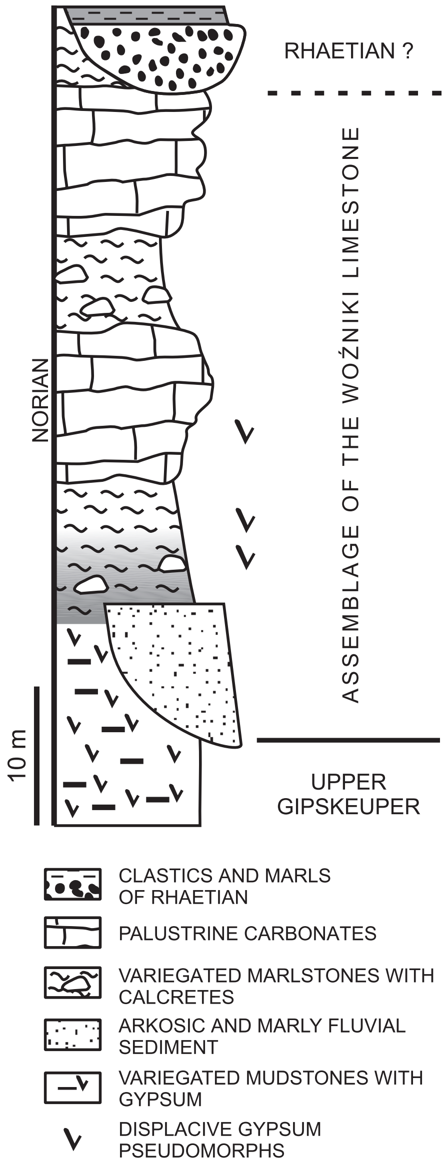

Figure 2. Lithostratigraphic log of the studied Upper Triassic interval.

We analyzed 41 samples from different localities (both drill holes and outcrops) palynologically in order to establish the age position of the studied succession by biostratigraphy. Most of the samples contained only opaque phytoclasts and occasional plant tissues in varying amounts, but were barren of palynomorphs. Only eight samples contained sufficient palynomorphs to allow a biostratigraphical classification. Preservation of the palynomorphs varied from poor to good.

RESULTS OF SEDIMENTOLOGICAL AND MICROFACIES STUDIES

Four basic facies types have been recognized within the described freshwater limestones: the travertine facies, the fluvial facies, the palustrine facies, and the pedogenic facies.

Travertines

Travertine facies have been found at three sites in the SE part of the basin (Fig. 1) and are represented by calcite fabrics precipitated directly in the spring orifice, and by spring-margin pool sediments where carbonates were deposited at a more moderate rate. The two subfacies differ slightly in the dominant fabric type.

The travertines that were formed in the spring orifices form either highly porous pure limestones composed of calcitic rafts and heavily calcified rhizomes and stalks (Fig. 6A) or are built by pisoids reaching 1 cm in diameter (Fig. 6B). The pisoids are in fact composed of microbial aggregates displaying faint concentric structure (Fig. 6C). The pisolites show common reversed grading and are interlayered with stromatolites (Fig. 6B). The latter are composed of dendritic shrubs of bacterial origin (Chafetz and Folk, 1983; Folk et al., 1985; Pentecost, 1990; Guo and Riding, 1994) or of filamentous fabrics (Fig. 6D). Trapped, calcified detritus of vascular plants is a common component of the spring travertines (Fig. 6E). Most of the encrustations are related to calcification driven by epiphytic microbial colonies covering the vascular plants.

The limestones that were formed in small pools in the marginal spring zone (Nowa Wieś Żarecka site) are also very rich in calcified algae and reed-like, vascular plants, but in contrast to the spring-mouth travertines, they also include finely laminated peloidal limestones (Fig. 6F). A rich microbial epiphytic assemblage (bacteria, cyanobacteria) enhanced the calcification of the higher plants (Fig. 6G). Moreover, thin calcitic rafts that formed at the surface of the pool water were probably related to activity of neustonic algal colonies (Fig. 6H) (Szulc, 1997). The travertines are devoid of clastic impurities, and the only noncarbonate components are minute quartz grains found in the travertines from the Poręba and Ogrodzieniec sites. In addition to the sites examined in this study, travertines were found by Roemer (1867) in the central part of the basin (see Fig. 1). From this travertine, Roemer described numerous molds of ferns (*Clathropteris* sp.), typical for the Upper Keuper.

Fluvial Facies

The fluvial deposits are generally represented by fine-grained clastics, mainly greenish and red mudstones with subordinate contribution of arkosic sandy material. These deposits occur as sheets interbedded within the carbonate packages of the Woźniki Limestone (Fig. 7A).

The fluvial deposits are mostly plane-bedded, cross-bedded, and rippled sandstones and siltstones (Figs. 7B and 7C). The primary structures are commonly obliterated due to postdepositional pedogenic processes; however, the dominant recognizable primary sedimentary structures include parallel lamination and ripple-drift cross-lamination. These structures suggest a sheet-like depositional system developed upon a low-relief mudflat area.

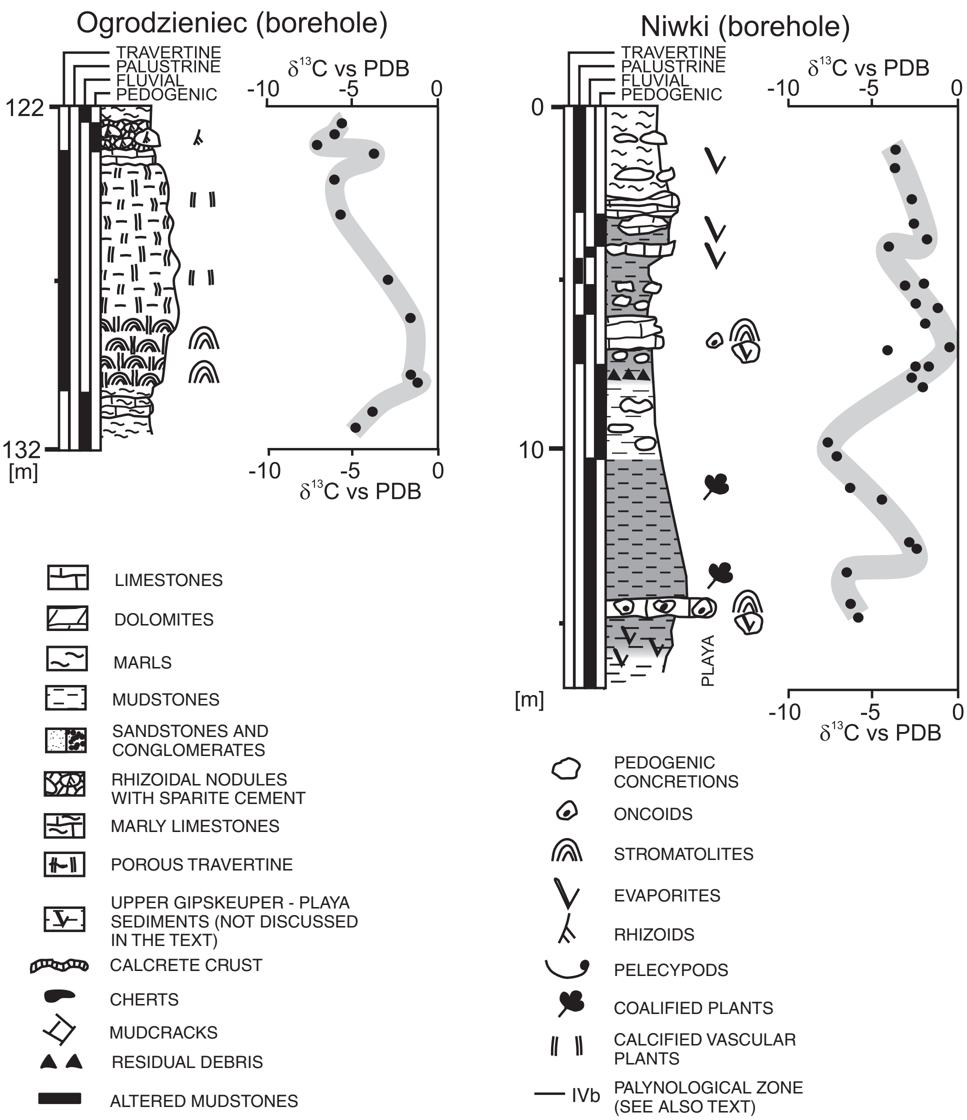

Figure 3. Measured sections and facies interpretation from boreholes Ogrodzieniec (travertine) and Niwki (transition from gypsiferous playa sediments to palustrine carbonates) with the $\delta^{13}C$ profiles. The shadowed parts of the profiles mark the gray to greenish sediment color. The nonshadowed part of the mudstones marks the red and brown color of the sediments.

Some of the beds have an erosional lower bounding surface, in particular the sheet-like gray, poorly sorted conglomeratic beds reaching up to 50 cm in thickness. The conglomerates consist of oncoids (Fig. 7D), coalified wood fragments (Fig. 7E), reworked pedogenic carbonate nodules (Fig. 7F), vertebrate bones and unionid bivalve debris (Fig. 7G). Such a composition indicates that the conglomerates originated as intraformational deposits through reworking and mixing of the material derived from pond sediments and paleosols by ephemeral streams operating upon the mudflat after heavy runoff events. Similar Triassic conglomerates composed by reworked calcretes have been described also by Gómez-Gras and Alonso-Zarza (2003) from Minorca and by Szulc (2005) from Upper Silesia.

The alluvium also encompasses black pebbles (Fig. 7H). The latter formed probably in small, poorly ventilated ephemeral pans where lithoclasts underwent impregnation by organic matter and were incorporated into fluvial sediments after redeposition (Strasser, 1984). Alternatively, the black pebbles might have originated due to local wildfires (Shinn and Lidz, 1987).

The main clastic mineral component is quartz, with subordinate contributions of clay minerals, K-feldspars, and carbonates. Among the clay minerals, illite, kaolinite, and very subordinate, mixed-layered illite/smectite have been detected (Lewandowska et al., 2001). The lowermost parts of the studied succession contain chlorite also. The clastic intercalations often show green or red color mottling, reflecting postdepositional pedogenic processes.

Palustrine Facies

The palustrine facies dominates among the freshwater sediments and comprises some 80 percent of the entire carbonate succession of the Woźniki Limestone. This facies is particularly well developed in the central part of the basin, i.e., between Cynków

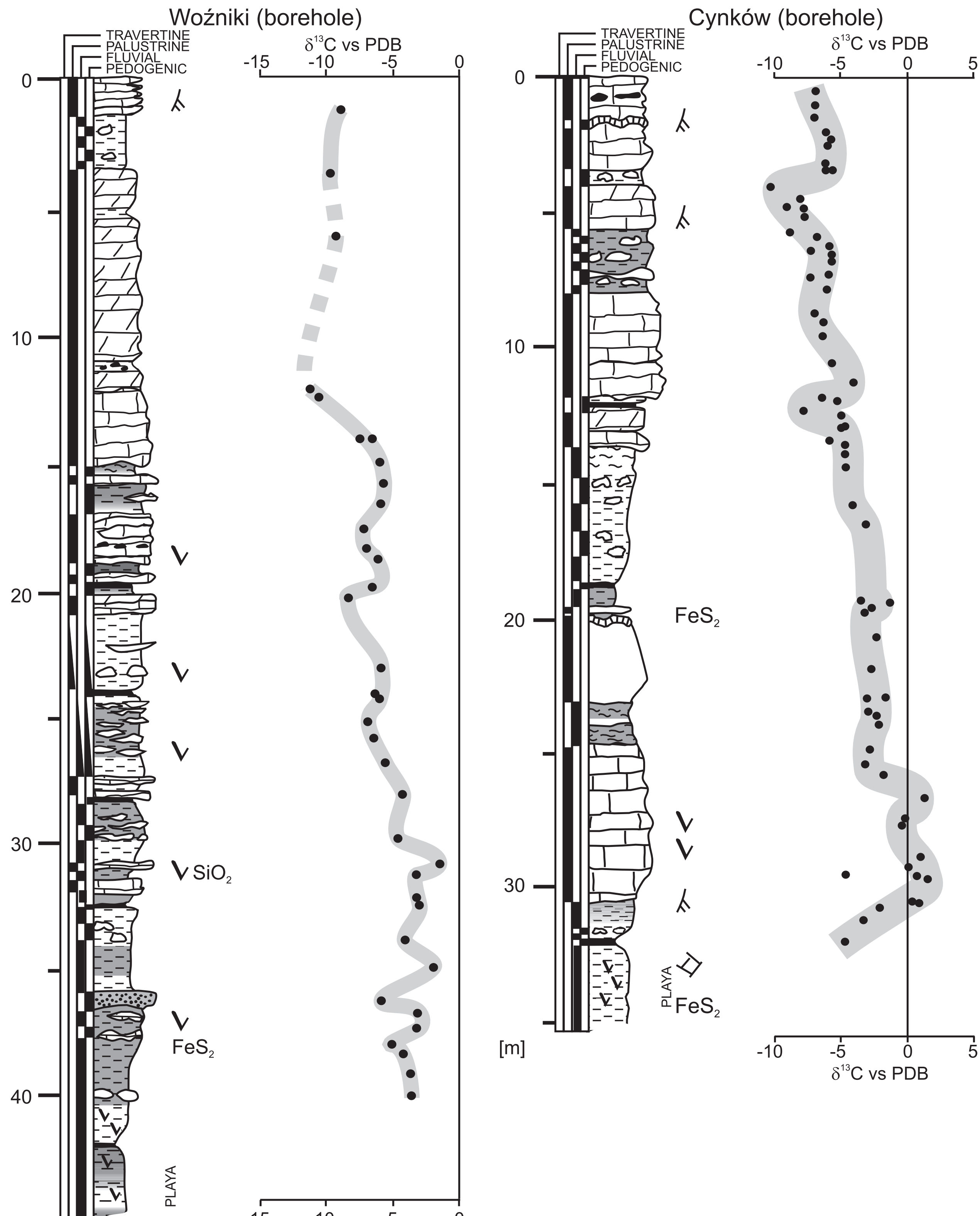

Figure 4. Measured sections and facies interpretation of the dominant palustrine carbonates from Woźniki and Cynków with the $\delta^{13}C$ profiles. For legend, see Figure 3.

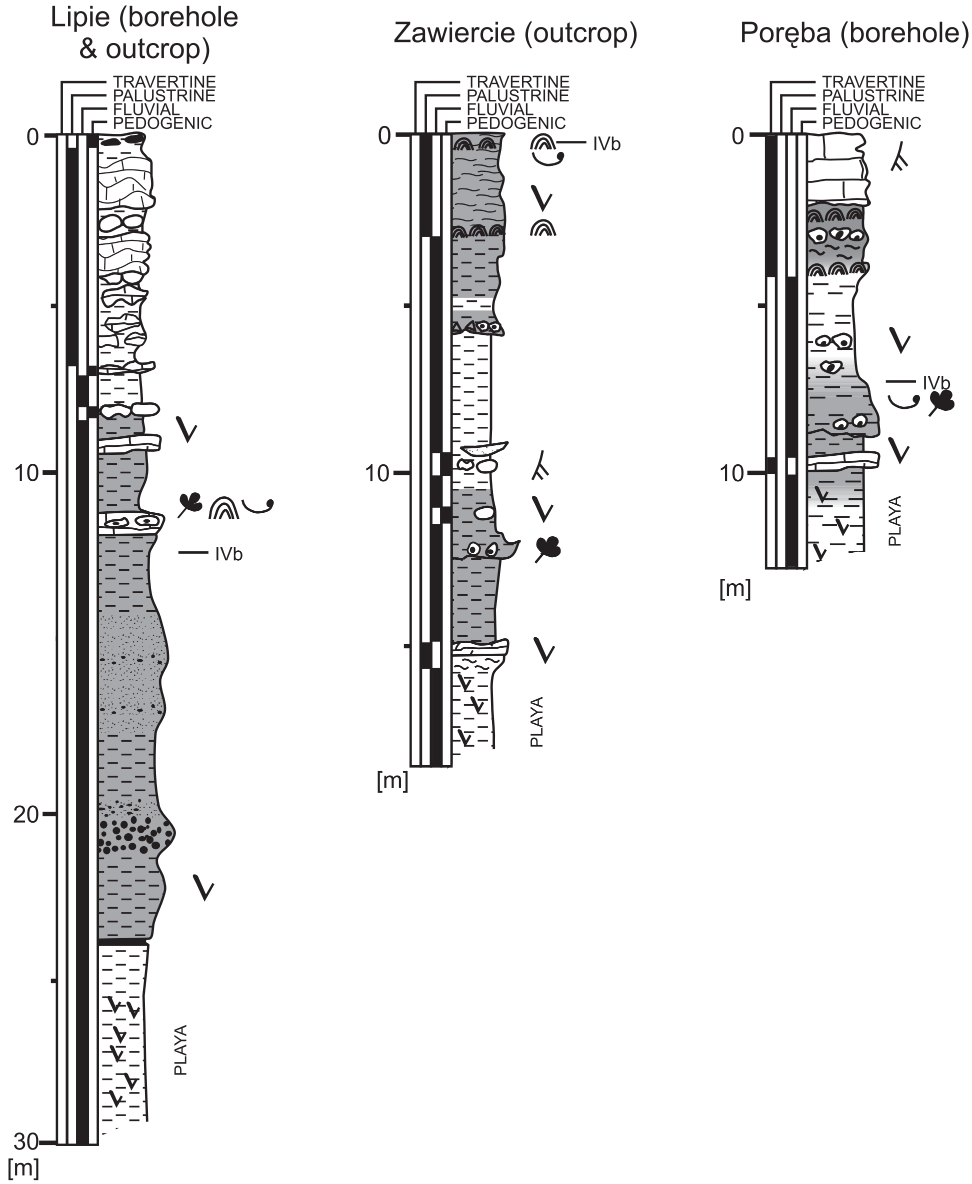

Figure 5. Measured sections and facies interpretation of the profiles from Lipie Śląskie, Poręba, and Zawiercie. For legend, see Figure 3.

and Psary (Fig. 1). The total thickness of the palustrine carbonates reaches 30 m (Fig. 4), but the carbonate succession is divided into two parts. This is particularly visible in the Cynków section, where the two palustrine carbonate packages are separated by 5 m of fluvial claystones and variegated mudstones (Fig. 4).

Palustrine carbonates are massive and/or faintly stratified white micritic limestones and rarely marls (Figs. 8A–8C). The faint stratification is accentuated by intraformational breccias, sheet cracks, calcrete crusts, teepee structures, or paleokarst horizons (Figs. 8A, 8C, 8D, and 8E). The larger karst cavities are commonly filled with clayey material, and the smaller voids are filled with internal silt and sparry cement (Figs. 8D and 8F). Some voids, in particular those related to rhizome systems, are filled with marcasite and pyritic encrustations (Fig. 8G).

The dominant microfacies type is homogeneous micrite with microgranular and clotted texture, which displays microscopic features, similar to the automicritic peloidal muds generated by bacterial mediation (Fig. 9) (Reitner, 1993).

The characteristics of the carbonate palustrine succession of the Woźniki Limestone show some obvious vertical changes. The lower part of the palustrine carbonates commonly contains pseudomorphs after dispersed crystals and aggregates of gypsum (Figs. 10A, 10B, and 10C). Rootlet fabrics are notably scarce in this part of the section. Upsection, the sulfates disappear, and the rhizoid fabrics become more common.

The palustrine lithologies are composed of low magnesian calcite. The noncarbonate components consist of clay minerals (up to 3 wt%) and quartz (<1 wt%). Among clay minerals, illite

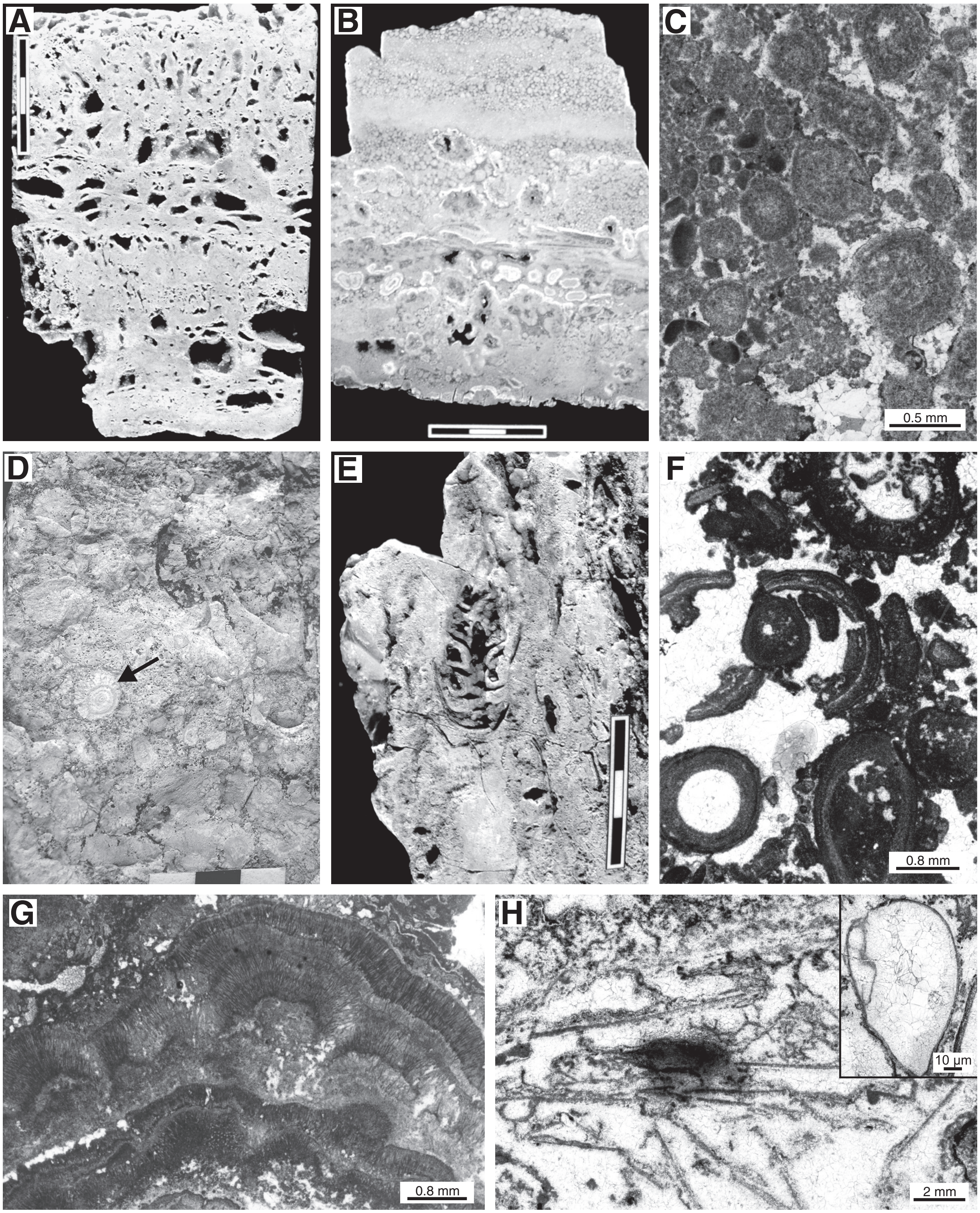

Figure 6. Spring facies. (A) Porous travertines with calcified stems of vascular plants and calcite rafts from the Ogrodzieniec borehole. Scale bar is 3 cm long. (B) Pisoidal and micropisoidal travertine from the Poręba site. Calcified debris of vascular plants is visible in the middle of the sample. Note the reversed grading of the pisolites. Scale bar is 3 cm long. (C) Microscopic view of the pisolitic limestones from B. The pisoids are composed of faintly laminated, clotted microbial grains. (D) Pisolitic-stromatolitic travertines from the Poręba site. The stromatolitic shrubs developed partly as overgrowths on the pisoids (arrow). Scale bar is 3 cm long. (E) Calcified cone mold embedded in the travertines from the Poręba site. Scale bar is 3 cm long. (F) Perpendicular section of the calcified reed-like stems from the spring-fed pools from the Nowa Wieś Żarecka site. (G) Microscopic view of the cyanobacterial mats building the stromatolite fabrics in the travertines from the Poręba site. (H) Calcite micritic rafts, partly broken and sunk, from the pool limestones, Nowa Wieś Żarecka site. (Insert) calcified, bubble-like neustonic algae (cf. *Botrydium* sp.) from the Nowa Wieś Żarecka site.

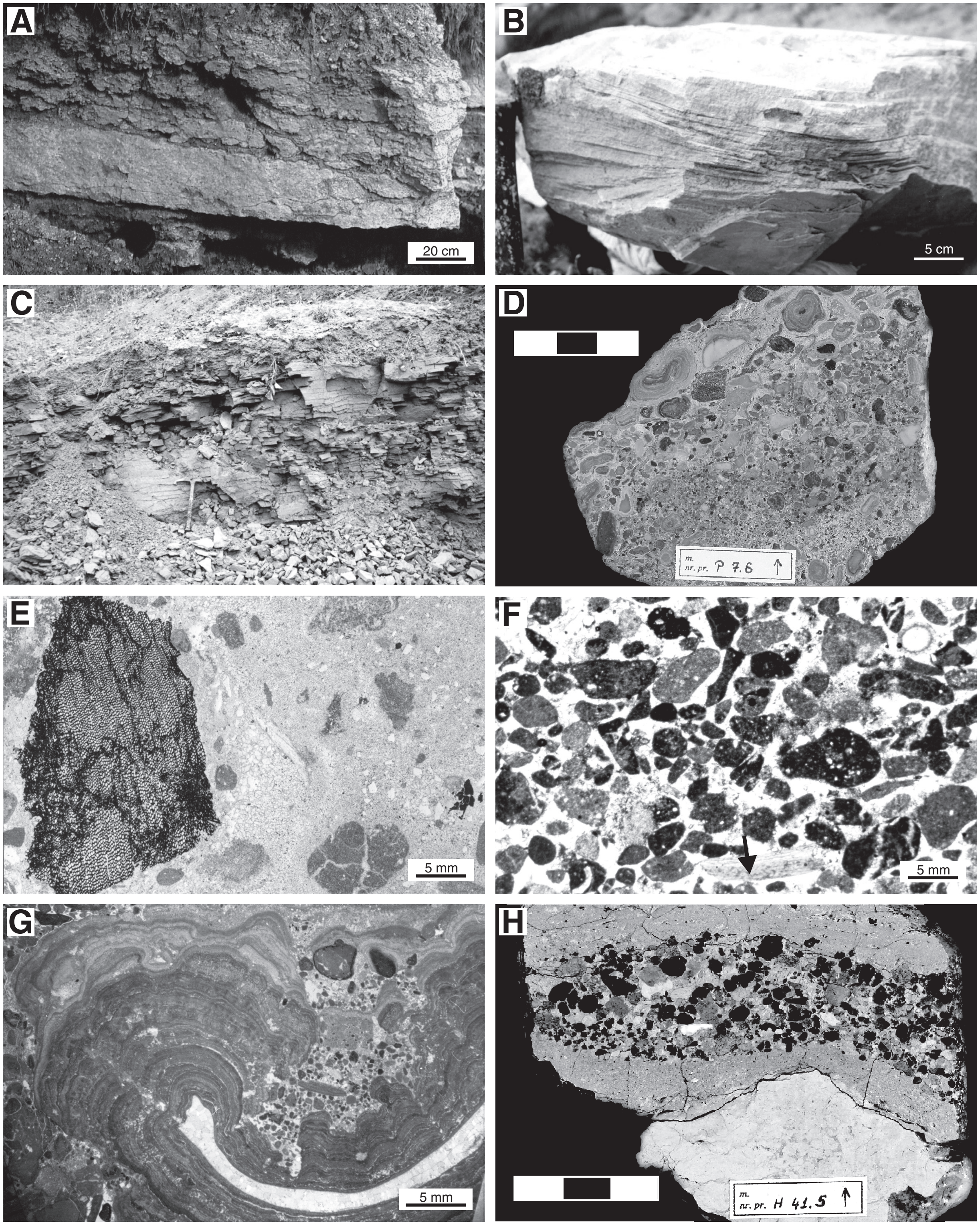

Figure 7. Fluvial facies. (A) Sheetflood, alluvial deposits with intraformational, conglomerates from the Woźniki site. (B) Cross-bedded, micaceous alluvial sandstones from the Lipie Śląskie site. (C) Plane-bedded, overbank muddy alluvial sediments from the Lipie Śląskie site. Hammer handle is 32 cm long. (D) Reversely graded alluvial sediments composed of oncoids, coal debris, and lithoclasts from the Poręba borehole. Scale bar is 3 cm long. (E) Coalified wood fragment and small lithoclasts. Thin section is from the sample in D. (F) Reworked pedogenic nodules, lithoclasts, bone fragments, and Chara gyrogonite. Thin section is from the sample in D. (G) Fragment of oncoid enveloping unionid shell. Thin section is from the sample is D. (H) Black pebble accumulation upon eroded palustrine limestones. Scale bar is 3 cm long.

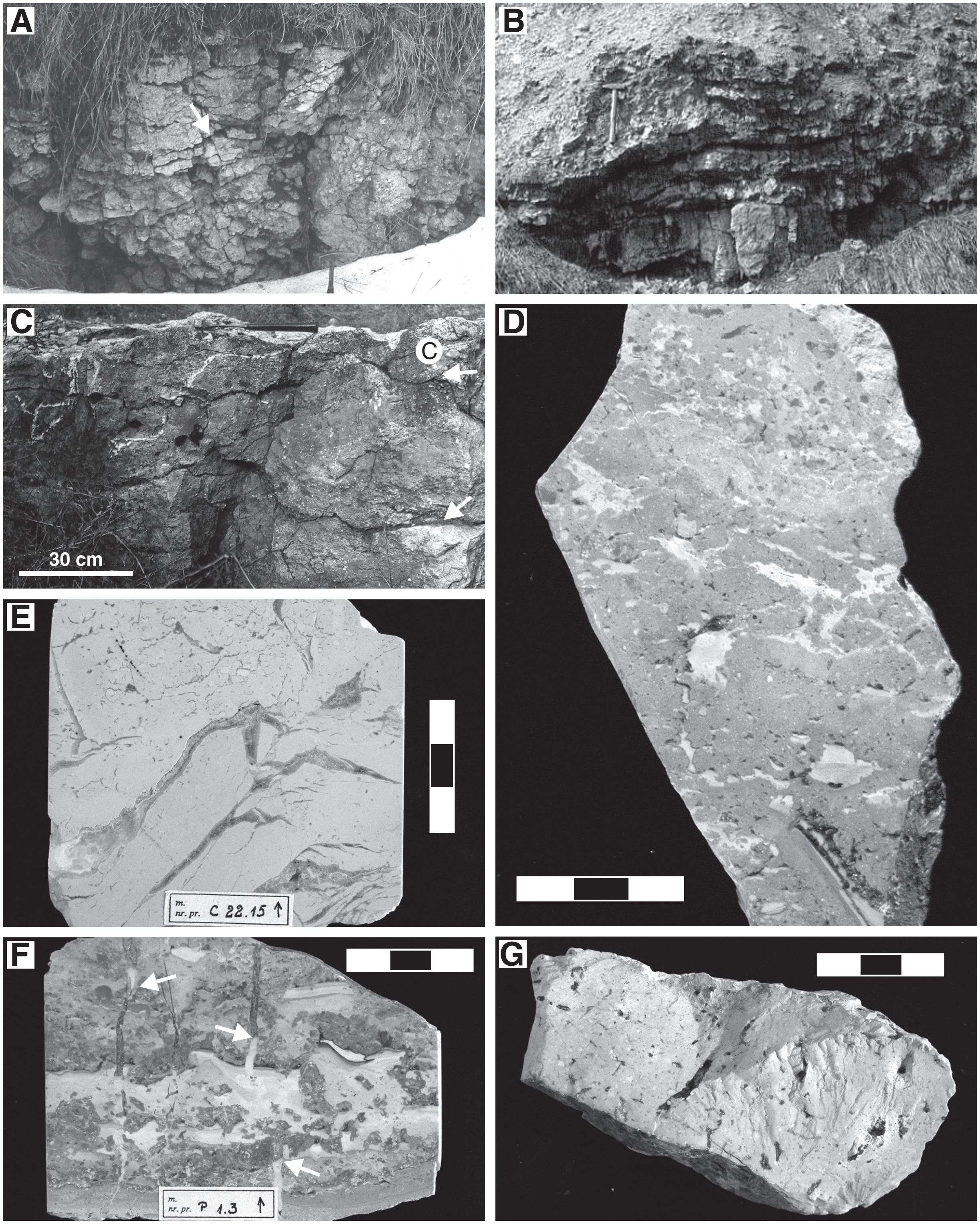

Figure 8. Palustrine facies. (A) Typical, faintly stratified palustrine carbonate deposits of the Woźniki Limestone from the Ligota site. Arrow indicates tepee deformation. Hammer for scale. (B) Thick- and medium-bedded palustrine limestones from the Lipie Śląskie site. Hammer for scale. (C) Massive palustrine limestones with karstic surfaces (white arrows) and calcrete crust at the top from the Cynków site. Note the uneven surface of the carbonate complex. (D) Planar cracks and microkarstic voids filled with internal silt and sparry cement from the Psary site. Scale bar is 3 cm long. (E) Small tepee deformation within the palustrine limestones from the Cynków borehole. Scale bar is 3 cm long. (F) Microkarstic cavities and dilatancy fissures (marked by arrows) filled with internal silt and sparry calcite, from the Poręba borehole. See text for further explanations. Scale bar is 3 cm long. (G) Massive palustrine limestones with root cavities encrusted by pyrite, from the Psary site. Scale bar is 3 cm long.

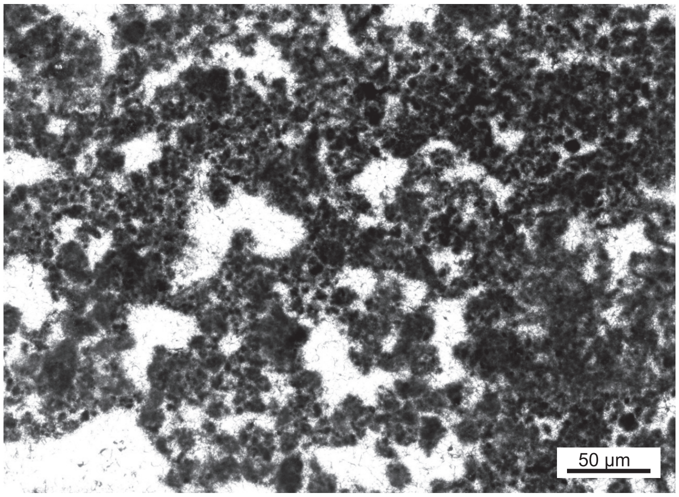

Figure 9. Palustrine facies. Microgranular, lumpy micrite probably of microbial origin (automicrite sensu Reitner, 1993).

is dominant, with secondary kaolinite and a very subordinate amount of mixed-layered illite/smectite. The clay assemblage is of detrital origin and does not differ from that of the adjacent alluvial mudstones and claystones.

It is noteworthy that the palustrine limestones underlying the clastic intervals (mostly of fluvial origin) are commonly dolomitized. Dolomitization may encompass a superficial layer of the palustrine limestone several centimeters thick (Fig. 10D), but may also extend as deep as 5 m from the top of the palustrine complex. The dolomitization created secondary porosity in the carbonates and produced yellow, vuggy horizons, called cellular dolomites (Figs. 10E and 10F), where the dolomite content can be up to 85 wt%. Microcrystalline, uniform dolomite dominates and replaces the calcite substrate pervasively. Most probably, the porosity was formed by replacement of limestone by the dolomite, followed and/or accompanied by dissolution of the non-replaced limestones. The pores are partly filled with fine clastic quartz and clayey interstitial sediments, indicating infiltration by meteoric waters. From the stable isotopes analyses (see following section), it can be concluded that the dolomite formed from solutions not subjected to evaporation. Taking this all together, the dolomitization was closely related to the subsoil processes (dissolution and precipitation) proceeding in the vadose zone (Sherman et al., 1962).

Within the palustrine facies, silicified horizons perfectly preserve the primary fabrics of the host carbonate sediments, including gypsum pseudomorphs, and encompass altered carbonates up to 50 cm thick (Fig. 10G).

Pedogenic Facies

The pedogenic sediments may be divided into soils developed on the clastic substrate (i.e., variegated mudstones and claystones) and carbonate soils (i.e., calcretes).

The first type encompasses a variety of paleosols from incipient, regolithic soils (Inceptisols) to more matured orders of Aridisols (sensu Retallack, 2001). This type of paleosol forms mainly brown, nodular and friable mudstones, reaching 1 m in thickness and passing gradationally to the underlying parent substrate. Some paleosols display relatively well-preserved root traces that diffusively penetrate the underlying host rocks. Pedogenic slickensides in the variegated mudstones are a fabric typical of semiarid Cambisol-Vertisol types of soil (de Vos and Virgo, 1969; Fitzpatrick, 1986; Retallack, 2001). The color mottling, typical for these paleosols, seems to reflect the early diagenetic oxidation of the hydrated Fe-oxides (gray colored) leading to mature Fe-oxides (hematite) and reddening of the primary gray sediments (Turner, 1980).

The carbonate soils (Calcisols), which have thicknesses ranging between several centimeters to 1 m, are developed either as pedogenic nodules and vadoids (coated grains of coated origin) entombed within clastic substrate (mainly weathered mudstones) or as various pedogenic fabrics developed upon the palustrine carbonates (Figs. 11A–11D and 11F). Both types of Calcisols display a wide spectrum of features diagnostic for their pedogenic origin, such as glaebules, circumgranular and septarian cracks, cutans, and root canals (Freytet and Plaziat, 1982) (see Figs. 11D and 11E). Upsection, the soils pass mostly into the palustrine carbonates, but sometimes they are covered by alluvial material.

Some of the palustrine limestone complexes are capped by massive calcrete of hardpan type (between several centimeters and 0.5 m in thickness) (Fig. 8C) or are intensively karstified. The surface of the karstified carbonates, as visible in the plane view, is jagged and features karst fabrics such as sinkholes up to 1 m in depth (Figs. 11F and 11G).

RESULTS OF STABLE ISOTOPES EXAMINATION

The paleoenvironmental reconstruction based on the carbon and oxygen stable isotope signals is consistent with the results of the sedimentological and petrographical studies. The stable isotope composition of the Woźniki Limestone generally follows the vertical and lateral variation of the sedimentary facies. Therefore, we discuss the diversity of stable isotope signals from various laterally equivalent facies and the isotopic variation as a result of the overall, secular paleoenvironmental changes in the region.

Facies-Dependent Isotope Composition (Lateral Fractionation)

By analyzing the spatial distribution of the stable isotopes in terms of the facies diversity, one may find a clear relationship between the facies type and stable isotope composition (Figs. 12A and 12B). The most positive values characterize the travertines from Poręba, (Fig. 12A), where $\delta^{13}C$ ranges between –0.3‰ and –3.5‰, and $\delta^{18}O$ ranges from –5.5‰ to –6.7‰.

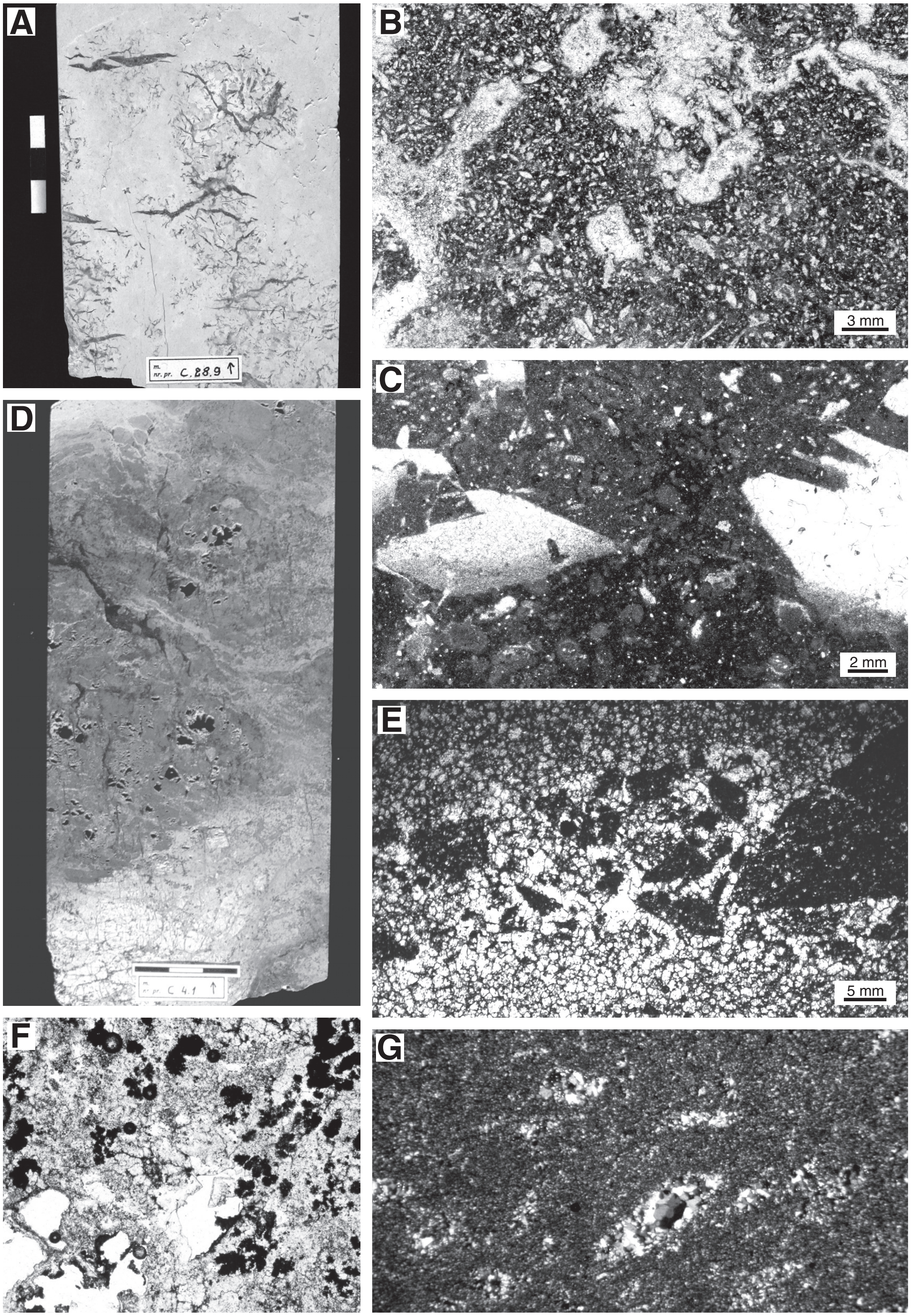

Figure 10. Palustrine facies. (A) Gypsum nests (pseudomorphed) within palustrine limestones from the Cynków borehole. Scale bar is 3 cm long. (B) Thin section from the sample in A. Note the displacive and enterolithic form of gypsum growth. (C) Secondary porosity after dissolved gypsum crystals. The voids are geopetally filled with internal silt and sparry calcite (from the Woźniki borehole). (D) Dolomitized palustrine limestones. The ochre staining (dark color at the photo) comes from Fe- and Mn-oxide impregnation (from the Cynków borehole). Scale bar is 3 cm long. (E) Thin section from the sample in D. (F) Highly porous ("cellular") dolomites with MnO-concentration (black spots). Thin section is from the sample in D. (G) Thin section of silicified, gypsum-bearing, palustrine carbonates from the Woźniki borehole.

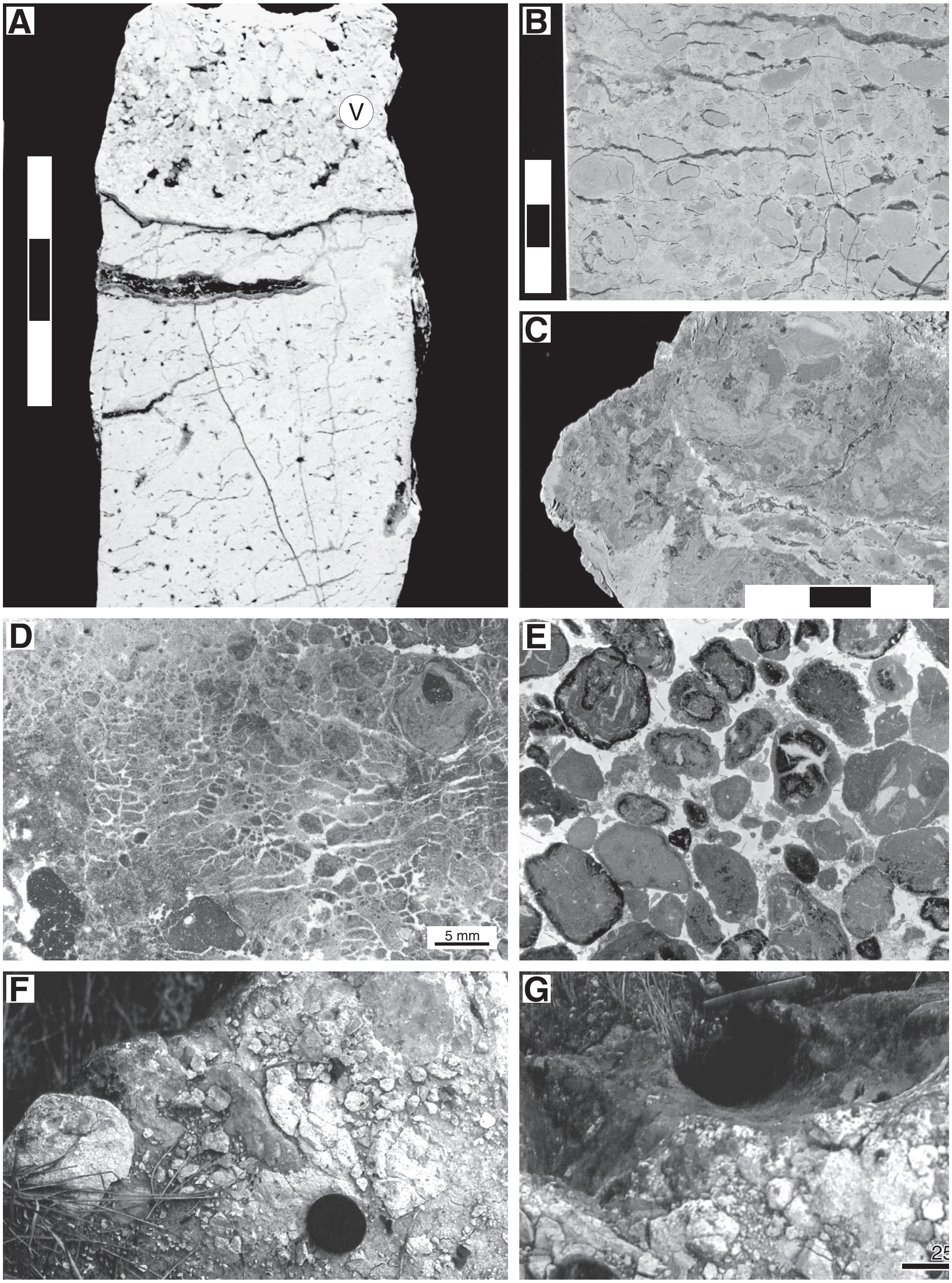

Figure 11. Pedogenic fabrics. (A) Pedogenic vadoid horizon (V) developed upon exposed palustrine limestones from the Brudzowice site. Note the planar cracks and rhizoid fabrics within the palustrine carbonates. Scale bar is 3 cm long. (B) Planar cracks and circumgranular, desiccation cracks featuring the exposed palustrine limestone from the Cynków borehole. Scale bar is 3 cm long. (C) Slab of the mottled pedogenic nodule isolated from the mudflat clastic sediments from the Zawiercie site. Scale bar is 3 cm long. (D) Thin section of paleosol carbonates with mottled fabrics and initial vadoidal cortex from the Psary site. (E) Thin section of paleosol glaebules with septaria from the Lipie Śląskie site. (F) Plane view of paleoweathering surface developed upon exposed palustrine limestones from the Cynków site. Lens cap is 55 mm across for scale. (G) Plane view of deeply karstified palustrine limestones from the Cynków site. Depth of the sinkhole reaches ~0.6 m.

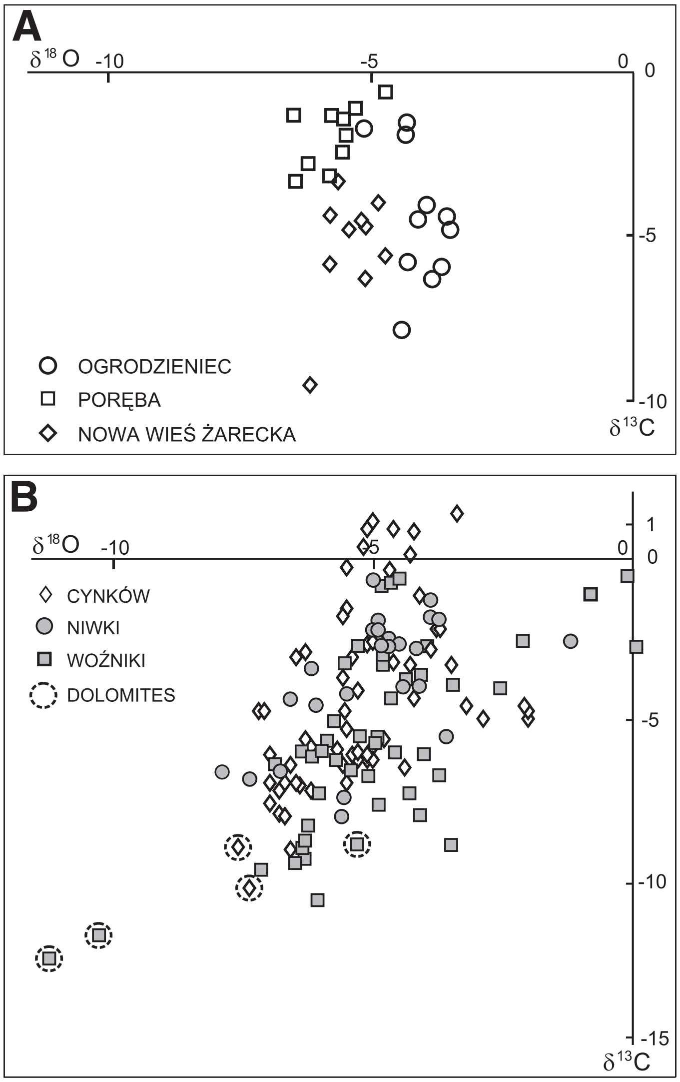

Figure 12. Cross-plot of δ^{13}C and δ^{18}O values for spring carbonates (A) and palustrine and pedogenic carbonates (B).

The carbonates that formed in the marginal ponds of the spring zone (Nowa Wieś Żarecka site) are lighter in δ^{13}C by some 2‰–3‰ than the travertines formed directly by the spring orifice. The range of δ^{18}O is very narrow and fluctuates between –4.8‰ and –6.2‰.

The stable isotope signals from the other facies (fluvial, palustrine, pedogenic) display a much wider range of values (Fig. 12B) since they were influenced by a broad spectrum of fluctuating environmental controls, particularly climatic. As in the travertines, the carbon isotope values exhibit a wider range (δ^{13}C values from –11‰ to 0.5‰ versus PDB) than the oxygen isotopes (δ^{18}O values from –8‰ to 0‰ versus PDB). Strongly negative excursions of δ^{18}O (to –11‰ versus PDB) are related to dolomitization proceeding under the influence of meteoric waters (Figs. 12A and 12B). Notably, a similar variation in the isotopic composition has been found in spring-related Upper Triassic freshwater carbonates in Wales (Leslie et al., 1992).

Evolution of the Stable Isotope Composition with Time

The δ^{13}C profiles from the three longest sections of the Woźniki Limestone (Niwki, Woźniki , Cynków) display a common trend, which undoubtedly reflects the longer-term environmental changes in the basin area (Figs. 3 and 4).

The fluvial sediments that formed during the wet, pluvial phase that preceded the deposition of the Woźniki Limestone carbonates show relatively negative δ^{13}C values, which might have been caused by a significant influx of meteoric water with isotopically light soil CO_2 derived from decay of rich plant debris. The subsequent abrupt positive shift toward a δ^{13}C range of 0‰ to +1‰ (PDB) accompanied the facies change from fluvial to palustrine, carbonate and/or sulfate deposition. Such a positive shift may be interpreted as typical for evaporitic enrichment in heavier isotopes. This in turn implies climate aridification. The covariant trend in δ^{18}O composition confirms this inference.

Subsequently, the δ^{13}C curve displays a gradual shift to more negative values. The isotopic trend is concurrent with a lack of sulfate minerals and the more common appearance of root systems. Therefore, we attribute it to a progressively more humid climate and a growing influence of the isotopically light carbon associated with meteoric water input and/or carbon derived from decayed organic matter.

The δ^{18}O does not display this apparent trend (Fig. 12). Unlike carbon isotopes, O-isotope fractionation is more sensitive to incidental factors such as short-term changes in evaporation and meteoric water influx. Pronounced negative shifts of δ^{13}C and δ^{18}O characterize the previously described dolomitized vuggy limestones. Such a negative shift indicates a definitive contribution of meteoric water and indicates that the dolomitization was related to the diluted water activity.

Long-term evolution in the travertine profile of Ogrodzieniec can also be observed. The observed gradual decrease in δ^{13}C values reflects changes of isotope contents in the parent solutions and/or migration of the spring orifice zone. Since the δ^{13}C covaries with the negative shift of δ^{18}O (Fig. 3), the observed trend most likely reflects the increasing contribution of the isotopically lighter, meteoric water to the formation of carbonates.

DISCUSSION OF THE ORIGIN AND GENETIC MODEL OF THE WOŹNIKI LIMESTONE

Paleohydrological and Tectonic Controls of the Origin of the Woźniki Limestone

Sedimentation of thick carbonate complexes of the Woźniki Limestone seems to be in contradiction to the arid and semiarid climatic conditions prevailing in Norian times, since deposition of such a voluminous carbonate body requires an adequate volume of the parent solutions. The apparent contradiction may be plausibly explained if one assumes a crenogenic, i.e., spring-related, alimentation model of the Woźniki basin as already postulated by Bogacz et al. (1970).

It is very interesting that the facies assemblage of the Woźniki Limestone has a paucity of lacustrine sediments, which are limited to deposits formed in small and shallow pools fed by spring water. Presently, these more resistant carbonates form gentle hills, whereas the fine clastics of the mudflat sediment adjoining to the limestone underwent erosion, giving a reversed pattern of the Late Triassic paleotopography. It seems that the Woźniki Limestone did not form one laterally continuous carbonate body, as suggested Gąsiorowski and Piekarska (1986), but rather represents a group of more or less isolated smaller patches of limestones, deposited in local swampy depressions maintained by a spring system. The travertines would be the spring-adjacent facies, while the distal facies are represented by palustrine carbonates.

As indicated by the stable isotopic data, the isotopic composition of the travertines differs from those of the other facies (Fig. 12). Lack of data on the original isotopic composition of the parent waters makes any further inferences, e.g., on the temperature of the water, uncertain. Recently, Słowakiewicz (2003) has claimed that all carbonates of the Woźniki Limestone are hydrothermal spring deposits. This conclusion is not reliable, since, as already discussed, the sedimentary facies context, biotic data, petrological and stable isotope signals, and the high temperature of the solution probably characterized only limited, spring-adjacent precipitated travertines. The other facies, such as the dominant palustrine one, include organisms (for instance, vascular plants and ostracodes) that do not have the ability to persist and develop in the temperature range (up to 97 °C) suggested by Słowakiewicz (2003).

As already noted the Woźniki Limestone is poor in fossils, particularly the palustrine facies, where only ostracodes have been found. Beside the ostracodes, one uncertain gastropod mold has been mentioned by Roemer (1867), who determined it as a possible *Paludina* sp.

The main reason for the paucity of biota is that the palustrine sediments formed under very stressed environmental conditions. The elevated alkalinity and salinity hindered colonization on one hand, and led to rapid degradation of the organic matter on the other hand. Also, the paucity of palynomorphs resulted from their degradation under high alkaline conditions. Moreover, the common occurrence of sulfide concretions (Fig. 8G) indicates that dysoxic conditions dominated in some poorly drained, waterlogged sediments.

Finally, since the basin was extremely shallow, the palustrine carbonates were desiccated very often. The environmental stress not only eliminated most of the organisms but also selected a very specialized group. A good illustration of such a selection is exemplified by the ostracodes. It is striking that most of the disarticulated ostracode tests have been found in voids developed within the sediments, i.e., below the sediment surface (Fig. 13). The ostracode colonies dwelt in the primary voids (i.e., root canals, sheet cracks). The subterranean, coenobiotic living strategy gave more chance for survival during the drought periods, since the wet conditions, supported by soil moisture and interstitial water, persisted there longer than in the superficial zone. On the other hand, the coenobionts may indicate contrasting hydrologic conditions between the dry surface and the subjacent, groundwater-soaked sediment column.

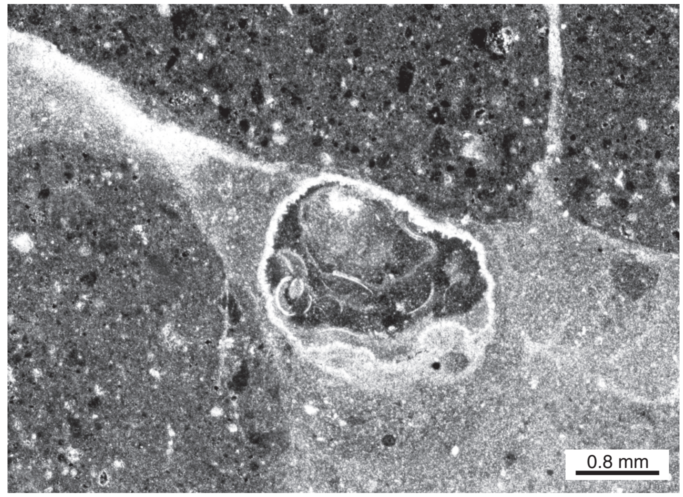

Figure 13. Thin section of root tube with disarticulated tests of coenobiotic ostracodes from the Psary site.

An endogenic origin of fluids is confirmed by distribution of the Woźniki Limestone, which is tightly bound to a master fault zone that might have provided a conduit for the ascending solutions. Typical carbonates of the Woźniki Limestone lie in a belt adjacent to the fault (Fig. 1) and do not occur outside this zone. Such a distribution confirms the inference about the endogenic origin and crenogenic nature of the solutions maintained in the basin (cf. Hancock et al., 1999).

The tectonic control of the spring distribution imposes some further constraints about the groundwater supply mechanisms. As a rule, fault-controlled springs are intermittently active (Sibson, 1987); hence, their efficiency fluctuates with time. In the studied case, the periods of water pumping in a given site might have alternated with weakening or even total vanishing of the source(s). This oscillation might have coincided with pulsing seismic activity. Small synsedimentary dilatancy cracks possibly record the paleoearthquake motion in the studied deposits (Fig. 8F), confirming this inference.

Climatic Controls

From the characteristics of the sedimentary complex of the Woźniki Limestone, one may infer that, aside from the endogenic factors, the sedimentary processes were also stimulated by alternating climatic conditions. The estimation of the climate significance is, however, more complex, since climatic influences may be overshadowed by endogenic ones.

Co-occurrence of the gypsum and limestones in the lower part of the succession indicates evaporitic precipitation under a negative precipitation/evaporation balance, which is typical for semidry climates (Figs. 3–5). The gradual withdrawal of the gypsum and the concomitant increasing occurrence of rhizoid fabrics observed upsection most likely reflect climate humidification.

Additionally, the previously discussed $\delta^{13}C$ curves indicate a similar trend, reflecting general climate pluvialization during the time under discussion. The “dry” facies of the Upper Gipskeuper were gradually replaced by more “wet” sediments typical for the Steinmergelkeuper facies in the entire Central European basin. This climatic trend was driven most probably by a drift of the mid-European block outside the subtropical dry belt, i.e., into the higher paleolatitudes (45–50°) (Szulc, 2007).

The paleoclimatic conditions in the Late Triassic also fluctuated in rhythms of shorter frequencies (Simms and Ruffel, 1990; Reinhardt and Ricken, 2000). The shorter-term changes are mostly attributed to the orbitally controlled fluctuation in paleomonsoonal circulation, which played an important role for the mid-European area in Triassic times (Kutzbach, 1994; Parrish, 1999). These short-term climatic changes are manifested, first of all, by alluvial clastic intercalations enclosed within the palustrine limestones. Also the karstification, certification, and dolomitization phenomena intimately related to clastic intervals mark breaks in carbonate sedimentation and subaerial weathering on one hand and indicate an increasing influence of meteoric waters (i.e., climate pluvialization) on the other hand.

The chert replacement of the calcite and sulfates most likely proceeded under fluctuating pH conditions, i.e., between the alkaline and the normal conditions when the dissolved silica was reprecipitated (Fig. 10G). This process may also be attributed to climatic fluctuations; during the dry periods, the evaporated solutions became alkaline, while the pluvialization led to a decrease in their alkalinity. If the subaerial exposure events coincided with dry climatic phases, the exposed palustrine limestones underwent pedogenesis.

Genetic Model of the Woźniki Limestone

As discussed already, the majority of the carbonates of the Woźniki Limestone is genetically related to solutions supplied by a huge spring system controlled by the active fault. As also noted, the fault-controlled spring activity fluctuated with time, so the history of Woźniki Limestone may be divided into periods of carbonate deposition and nondeposition. The lithological succession of the Woźniki Limestone indicates, however, that the endogenic cycles were also being modified by climatically controlled factors (clastic input, pedogenic alternation, karstification) superimposed upon the endogenic mechanism.

Lithological variation (i.e., limestones vs. clastics) within the Woźniki Limestone rock assemblage necessitates a changing ratio of the endogenic versus meteoric solutions supply. We can envision four scenarios of this interplay:

Scenario 1. Endogenic Alimentation Active, Climate Arid

During the dry periods, the carbonates (and gypsum) precipitated from the crenogenic, undiluted solutions.

Scenario 2. Endogenic Alimentation Ceased, Climate Semiarid

Carbonate deposition stopped and calcrete formed.

Scenario 3. Endogenic Alimentation Ceased, Climate Wetter

Carbonate sedimentation stopped, and karstification became a particularly important process affecting the limestones. Dolomitization progressed.

The intimate association between detrital sedimentation and dolomitization processes suggests that the dolomitization was driven by an increase of the meteoric water input during humid periods. If the pluvial period was prolonged, some silicate minerals (feldspars, chlorite) underwent alteration and released (among others) Mg^{2+}. This led to dolomitization of the karstified palustrine limestones. The inference is also supported by the stable isotopes data. The proposed dolomitization model is contrary to those reported from similar continental settings where calcite-to-dolomite transformation is attributed to fluids evaporated under arid climatic conditions (Richter, 1985; Spötl and Wright, 1992; Colson and Cojan, 1996; Warren, 1999; Sinha and Raymahashay, 2004).

Scenario 4. Endogenic Alimentation Active, Climate Wetter

In this scenario, the denudation processes prevailed. The muddy and clayey sediments derived from outside the spring zone were eroded and redeposited. This process led to clastic dilution of the carbonate-bearing source waters and hindered unconstrained precipitation of $CaCO_3$.

To summarize, as the presented data suggest, the switch between the carbonate and clastic sedimentation may be plausibly explained as an effect of climatic fluctuations between the dry and pluvial periods (Fig. 14). The dry periods favored deposition of carbonate sediments (travertines and palustrine limestones, calcretes), while the pluvialization obstructed carbonate sedimentation and promoted their denudation, dolomitization, and replacement by fine-grained, detrital deposition. This model is supported by the clay mineral composition. The clay minerals enclosed in the carbonate deposits are dominated by illite, which is characteristic of drier conditions, whereas the clastic, fluvial intercalations display increasing contribution of kaolinite, which forms preferably under humid conditions (Ruffel et al., 2002).

Palustrine facies are commonly defined as subaerially transformed lake-margin deposits (see discussion in Alonso-Zarza, 2003). This definition is, however, difficult to apply for cases where the palustrine environment is not preceded by a lacustrine stage, as in this case. The most probable sedimentary environment of the Woźniki Limestone would be a low-relief area with swampy depressions filled with gradually evaporated water. The paucity of typical lacustrine sediments and fossils indicates

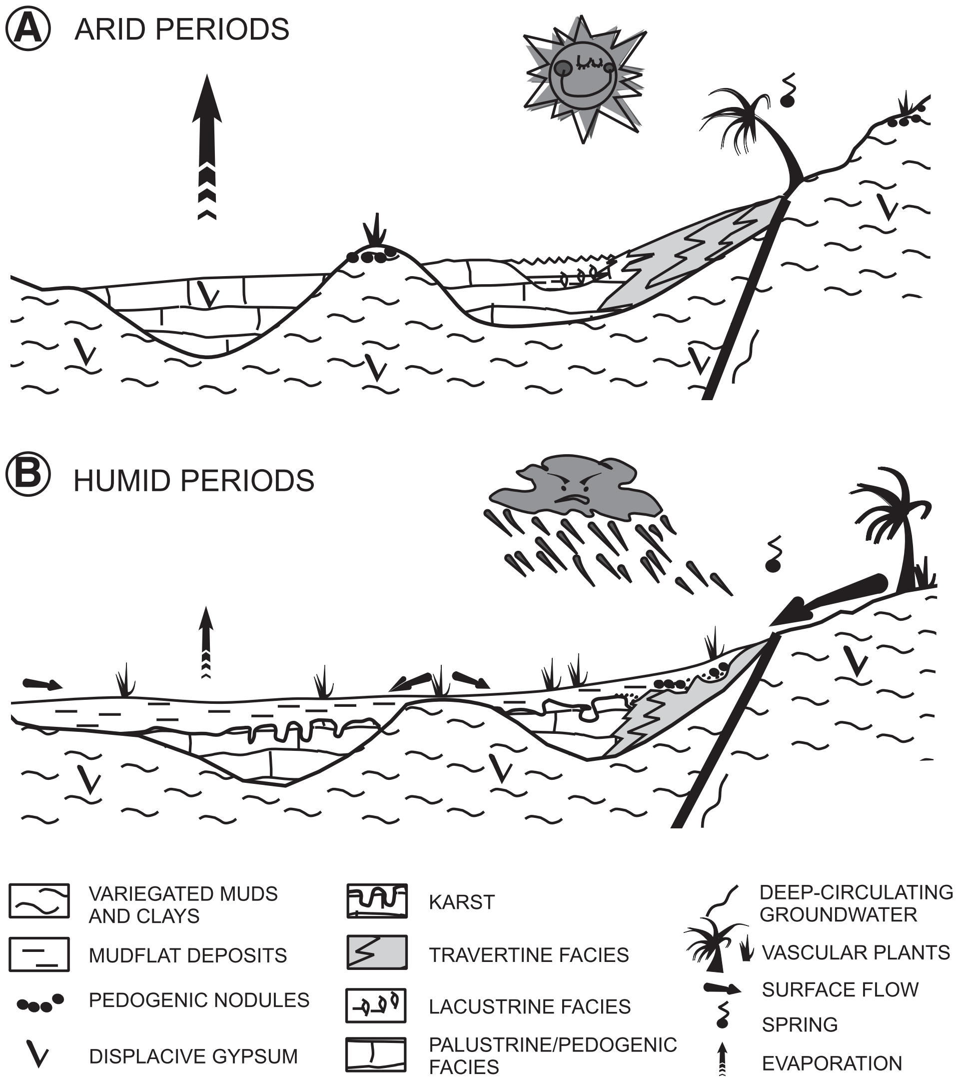

Figure 14. Genetic model of the Woźniki Limestone. (A) Deposition of the limestone during arid periods. (B) Degradation of the limestone and alluvial sedimentation during humid periods.

that limnic conditions were limited to very small and ephemeral ponds. Similar palustrine basins have been interpreted either as floodplain ponds (Huerta and Armenteros, 2005) or as groundwater wetlands (Tandon and Andrews, 2001). In both cases, the basins would have been maintained by meteoric and fluvial waters. The specific character of the palustrine Woźniki Limestone depends on the crenogenic recharge system maintaining the basin. The endogenic nature of the water supply resulted in an unconventional relationship between the climate and continental carbonate sedimentation. In contrast to the typical situation, the crenogenic palustrine carbonates developed in arid conditions, and they vanished with climate pluvialization.

CONCLUSIONS

The Upper Triassic (Norian) Woźniki Limestone from Upper Silesia is composed of freshwater carbonate sediment formed in swampy depressions, fed by a huge, fault-bound spring system. The travertines formed adjacent to the spring orifices, while in the more distal area, the palustrine carbonates were deposited.

The crenogenic character of the solution supply imposes a very specific model of palustrine carbonate sedimentation. The pure carbonates formed mainly during dry intervals, whereas the climate pluvialization involved meteoric and clastic dilution and the final withdrawal of calcareous deposition. This model is opposite to some extent to the typical model of freshwater carbonate sedimentation under humid conditions, which ceases, in turn, under dry climatic conditions. The model presented here is supported by geochemical signals and biotic indicators. It is remarkable that the limestones are very poor in fossils (both faunal and floral), which are more common in the fluvial (humid) intervals.

In addition to the shorter pluvialization episodes, a secular trend in climate humidification has been identified. This trend reflects a general climate evolution forced by drift of the central Europe block to the higher paleolatitudinal zone.

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