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FACIES DEVELOPMENT AND SEDIMENTARY ENVIRONMENTS OF THE CARPATHIAN KEUPER DEPOSITS FROM THE TATRA MOUNTAINS, POLAND AND SLOVAKIA

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Abstract: The lower-middle Upper Triassic succession of the Fatricum domain from the Tatra Mts is commonly called the Carpathian Keuper. During the Late Triassic, the Fatricum Basin was a proximal part of the central Inner Carpathian Basin. In early Carnian times, carbonate sedimentation stopped. Emersion of the Middle Triassic carbonate platform resulted in development of palaeokarst and pedogenic fabrics and deposition of conglomerates. Typical Carpathian Keuper sediments – variegated shales with intercalations of sandstones and dolomites represent mixed continental/shallow marine environments. Variegated mudstones with pedogenic carbonate concretions and intercalations of thin sandstone beds originated in mudflat environment under the semi-arid climate condition. Thick-bedded, cross-stratified sandstones with common plant debris represent fluvial deposits. They were deposited during the periods of climate pluvialisation. According to $\delta^{13}C$ and $\delta^{18}O$ data, thick, continuous dolomitic sediments containing local cherts represent marine sediments of perilittoral environments, which were commonly emerged as evidenced by common palaeokarst and palaeosols featuring these complexes. Cyclicity in the lower part of the Carpathian Keuper resulted from climatic changes, whereas dolomite-clastic cycles from the upper part of the succession were generated probably by sea level fluctuations. Moreover, deposition of the Keuper succession was controlled by synsedimentary tectonics which resulted in big facies variability.

Key words: Carpathian Keuper, Triassic, Fatricum, sedimentary environments, Tatra Mountains.

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INTRODUCTION

Sedimentary environments of the Upper Triassic of the Fatricum Basin are poorly recognized mainly because of small and scattered outcrops. Therefore reconstruction of complete facies succession is difficult. Moreover, intense facies change and complex tectonic structure of the study area impedes unequivocal correlation of lithostratigraphic profiles throughout the basin.

The Upper Triassic succession from the Krížna Unit (Fatricum domain) of the Tatra Mts overlies a 400 m thick carbonate complex of the Middle Triassic. The succession is composed mainly of mixed clastic/carbonate sediments formed in continental and shallow marine environments and it is called as Carpathian Keuper. The discussed deposits accumulated in the Fatricum Basin which was a part of the Western Tethys.

The present paper has three objectives: (1) to present a description of main lithofacies complexes of the Carpathian Keuper; (2) to present the reconstruction of their sedimentary environments; and (3) to propose main stages of the Keuper sedimentation with reference to palaeoclimate changes.

GEOLOGICAL SETTING

The Tatra Mts (Fig. 1) are the highest and northernmost massif of the western Inner Carpathians. It is built of the Variscan crystalline core and the Mesozoic sedimentary cover, which includes several nappes. The lowermost nappe (so called High Tatric Nappe) belongs to the Tatricum domain (Andrusov *et al.*, 1973; Kotański, 1979a, b).

The High Tatric Nappe is overlain by the Sub-Tatric nappes. The lower one is the Krížna Nappe, which together with Vysoká Nappe from the Male Karpaty Mts represent the Fatricum domain (Andrusov *et al.*, 1973). The Krížna Nappe of the Tatra Mts contains sedimentary rocks from the Lower Triassic to middle Cretaceous. The Krížna Nappe is overlain by sedimentary rocks of the Choč Nappe, which

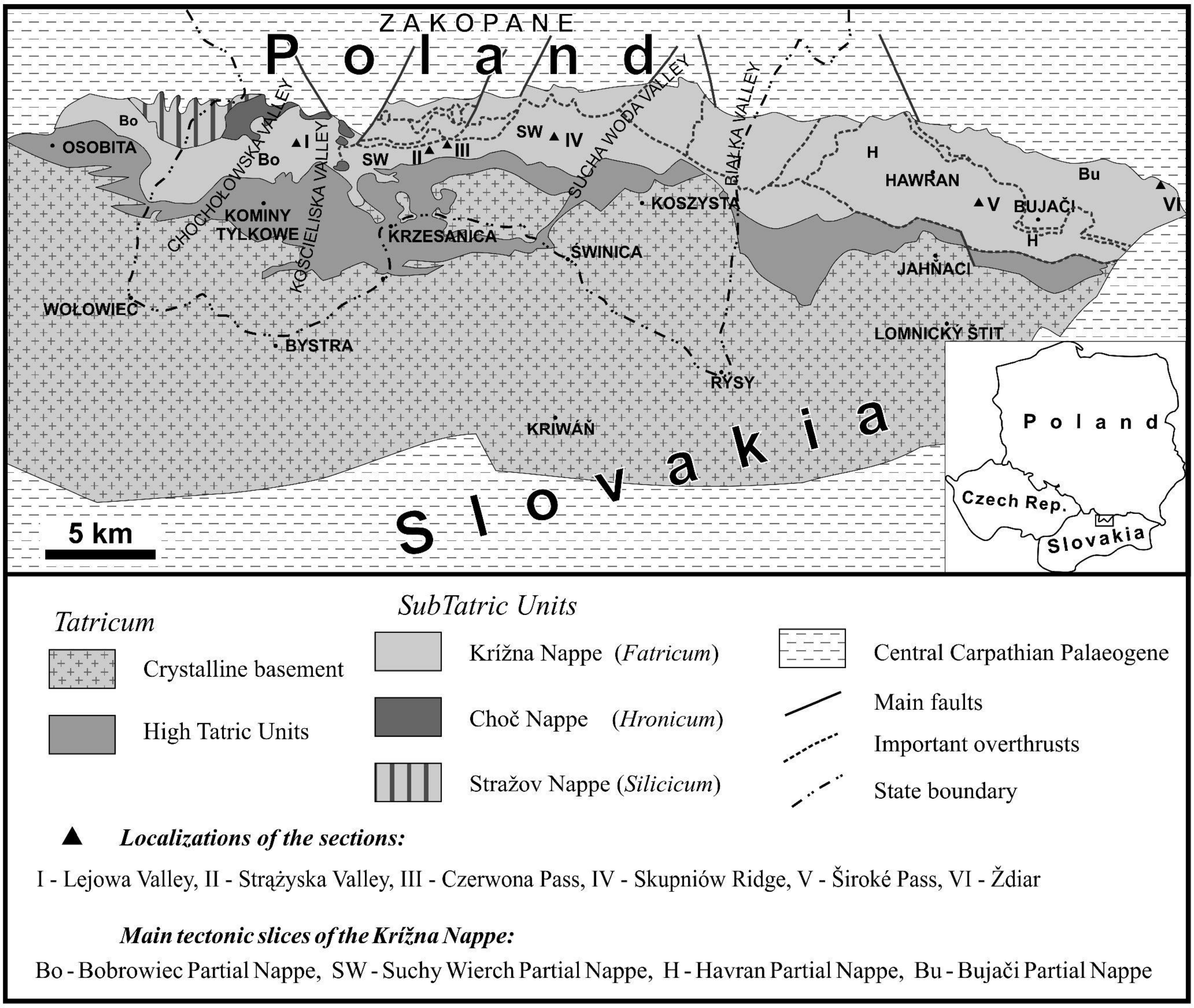

Fig. 1. Tectonic map of the Tatra Mts (after Bac-Moszaszwili *et al.*, 1979; modified)

represents Hronicum domain. Kotański (1973, 1974, 1986a, b) suggested also existence of the uppermost Stražov Nappe (Silicicum domain), which contains only the Middle-Upper Triassic sediments. All the nappes are covered by the Inner Carpathians Palaeogene.

The Krížna Nappe in the Tatra Mts is divided into several smaller nappes and slices (Goetel & Sokołowski, 1929; Guzik, & Kotański, 1963a, b, Kotański, 1979a; Bac-Moszaszwili, 1998; Bac-Moszaszwili & Lefeld, 1999; Lefeld, 1999; Birkenmajer, 2000; and others).

The lower part of the Upper Triassic (Carnian–Norian) of the Fatricum domain is distinguished as an informal stratigraphic unit called the Carpathian Keuper since it displays a similar facies as in its Germanic equivalent. The Carpathian Keuper is built of variegated shales with dolomite concretions, sandstones, conglomerates and dolomites. Limanowski (1903) interpreted the variegated shales as continental sediments with important contribution of fluvial sandstones. Turnau-Morawska (1953), who has done petrographical study on the Carpathian Keuper, interpreted red and green shales and dolomites as marine sediments, while the sandstones and conglomerates as fluvial deposits. She also noted that the Keuper deposits display variable thickness throughout the unit, with a maximum reaching ca 300 m. Borza (1959) provided another petrographical analysis and some remarks on sedimentary environment of the Keuper from the Slovak Tatra Mts. He interpreted the sediments as fluvial, partly shallow marine deposits and postulated primary origin of the Keuper dolomites. Clay minerals of the Keuper point to fluvial to shallow marine environment (Al-Juboury & Durovič, 1992). According to Al-Juboury and Durovič (1996) the dolomite deposits formed under hypersaline conditions.

Lack of index fossils caused the Carpathian Keuper biostratigraphy very vague. In the black mudstones of the Keuper some spores and pollens of ferns and club moss were found (Fijałkowska & Uchman, 1993). They date the Keuper black mudstones (for instance from Czerwona Pass site) as the late Keuper.

METHODS

Six, better exposed sections of the Carpathian Keuper from the Polish part of the Tatra Mts – Lejowa Valley (Dolina Lejowa), Strążyska Valley (Dolina Strążyska), Czerwona Pass (Żleb pod Czerwoną Przełęcz), Skupniów Ridge (Skupniów Upłaz), and two sections from the Slovak Belanské Tatra Mts – Ždiar and Široké Pass (Široké Sedlo) were measured and sampled. Polished slabs and thin sections have been made from selected samples. A petrographic microscope was used for recognition of microfacies. Selected samples have been also observed under the SEM.

Samples of lutite carbonates were used to determine the content of stable isotopes. The values of $\delta^{13}C$ and $\delta^{18}O$ were determined using measurements made with SUMY mass spectrometer at the Institute of Geological Sciences, Academy of Sciences of Belarus at Minsk. Every sample was treated with 100% orthophosphoric acid and then carbon dioxide was collected in a trap with liquid nitrogen and purified in vacuum. The measurement error was ±0.2 ‰. Both C and O isotope ratios are presented in reference to the PDB standard.

RESULTS

Description of the sections

The studied sections represent various intervals of the Upper Triassic succession. Three sections (Skupniów Upłaz, Strążyska Valley and Široké Sedlo) comprise the sedimentary transition between Upper Ladinian and Carnian. Three sections (Ždiar, Lejowa Valley and Czerwona Pass) encompass middle interval of the Keuper succession. Two latest of them include also the transition to the Rhaetian Fatra Formations (Gaździcki, 1974; Michalík & Jendrejáková, 1978).

Lejowa Valley (LS) (Fig. 2)

The section belongs to the Bobrowiec Partial Nappe (Andrusov, 1959). It is composed of several measured partial sections (Fig. 2). Variegated shales with dolomite intercalations dominate all the section. The lower part of the section is composed of thick-bedded dolomites with cherts. The cherts range from some centimetres up to 1 m in size. The overlying part of the section is characterized by typical development of the Carpathian Keuper facies, that is by variegated mudstones with thin layers of dolomites and dolomitic concretions. Thin-bedded sandstones seem to be subordinate. Organodetrital limestones and black shales with bivalves from the upper part of the LS section belong already to the Rhaetian. Total thickness of the section exceeds 130 m.

Strążyska Valley (SV) (Fig. 3)

The section belongs to the Suchy Wierch Partial Nappe. It begins with regolith of the Upper Ladinian dolomites, covered by yellowish mudstones with marls. Above them grain-supported conglomerates, which consist of carbonate pebbles reaching 5 cm across, occur (Fig. 4A). The conglomerates grade into red and violet mudstones. The mudstones are overlain by coarse-grained sandstones. The upper part of the outcrop is built of dolomites, which are replaced by quartzites in the uppermost part. The section is about 14 m thick.

Czerwona Pass (CP) (Fig. 5)

The section belongs to the Suchy Wierch Partial Nappe. In spite of some gaps, it is one of the best exposed out Carpathian Keuper section in the Polish Tatra Mts. It begins with dolomites with lenses of mudstones containing carbonized flora remnants. Dolomites comprise fauna: ostracods and sponges. Upward, dominate shales, which include intercalations of green sandstones with pedogenic fabrics (Fig. 6D–F) and carbonized floral remnants. Above the palaeosol, about 3 cm-thick layer of coal developed. In the middle part of the section, 30 cm-thick layer of polymictic conglomerates with carbonate and quartzite pebbles (up to 5 cm across) are present. They contain fragments of carbonized wood (Fig. 7D).

The overlying green sandstones, intercalated with dark, organic rich shales comprise fine plant detritus. Above this lies a thick complex of red shales with dolomitic nodules. The shales are replaced by light coloured dolomites comprising marine fauna, including bivalves (Fig. 8B) and sponges (Fig. 9). The marine fauna (benthic foraminifers – Fig. 8C) occurs also in the thinner dolomitic beds, intercalating the overlying red shales. The uppermost part of the section is composed of yellow and black shales and organodetritic limestones, which represent most probably the Rhaetian. The CP section is about 55 m thick.

Skupniów Ridge (SU) (Fig. 3)

This section belongs to the Suchy Wierch Partial Nappe (Goetel & Sokołowski, 1929). It is well outcropped along the tourist trail at the northern part of the Skupniów Upłaz ridge. A thick complex (ca 400 m) of Middle Triassic dolomites is overlain here by three beds of rubbled dolomites with cherts. They are intercalated with yellow shales, comprising dolomitic concretions (see Fig. 6C). Yellowish shales continue upsection and are replaced by coarse-grained, thick-bedded sandstones with carbonate cement. The sandstones are, in turn, overlain by variegated shales. They comprise intercalations of cross-stratified, thick-bedded quartzitic sandstones, but this part of the section is tectonically deformed and poorly outcropped. The measured profile from the lower part of the section is ca 14 m thick.

Široké Pass (SS) (Fig. 3)

The section belongs to the Havran Partial Nappe *sensu* Sokołowski (1948) (Belanske Tatra Partial Nappe *sensu* Bac-Moszaszwili & Lefeld, 1999 and Lefeld, 1999). The lower part of the section is well outcropped in the eastern side of the Szeroka Bielska Pass, while the upper part is covered by soil. The section comprises carbonate rocks of the uppermost Ladinian and the clastics of the lowermost Keuper (Fig. 10A). The lower part of the section is built of well bedded dolomites with stromatolites, evaporite pseudomorphs and tepee structures. There are common intercalations of thin tempestites. The uppermost part of dolomitic beds is commonly silicified. Dark limestones with pedo-

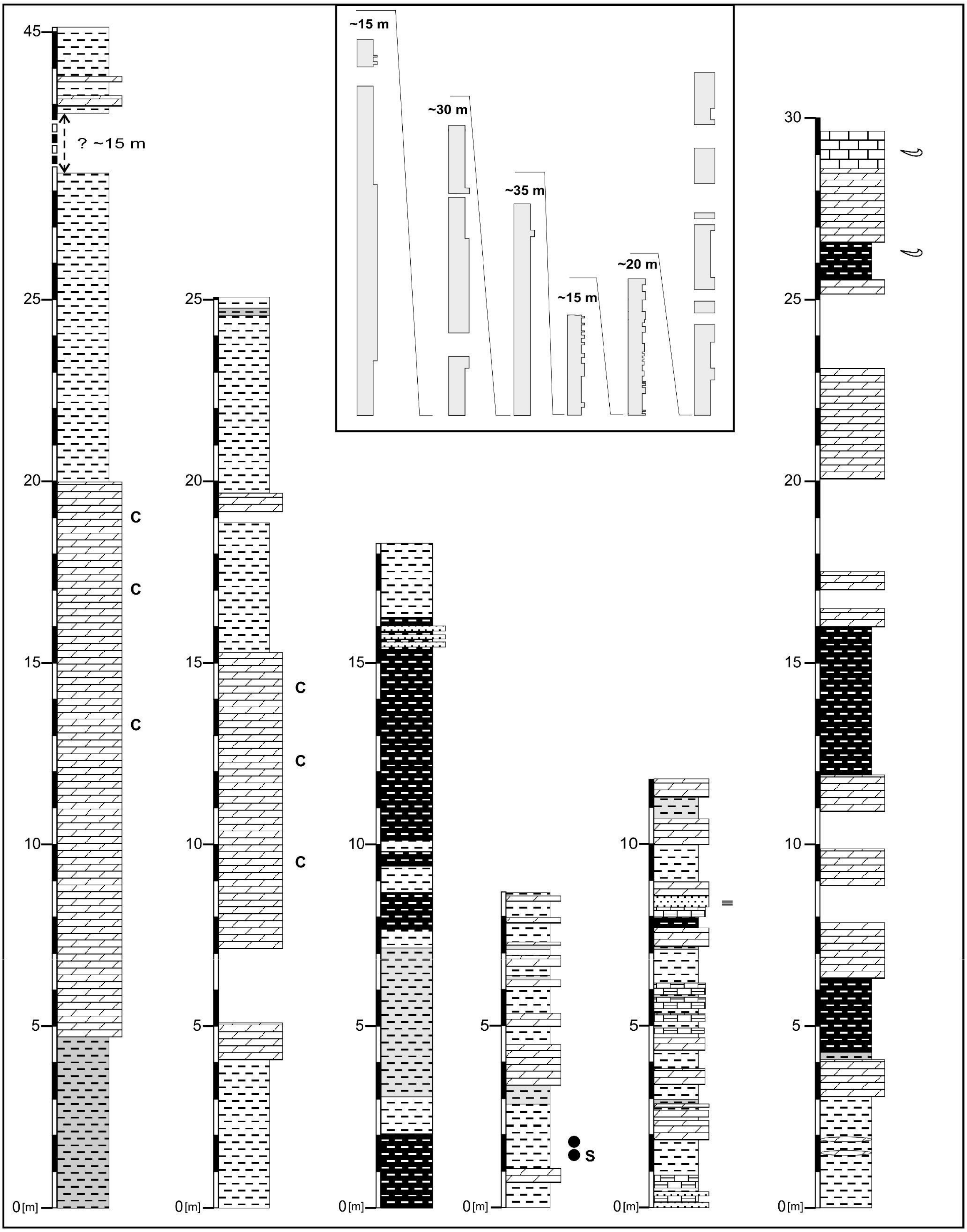

Fig. 2. Synthetic sections of the Keuper facies from LS section. Stratigraphical order from the left to the right; see Fig. 3 for legend

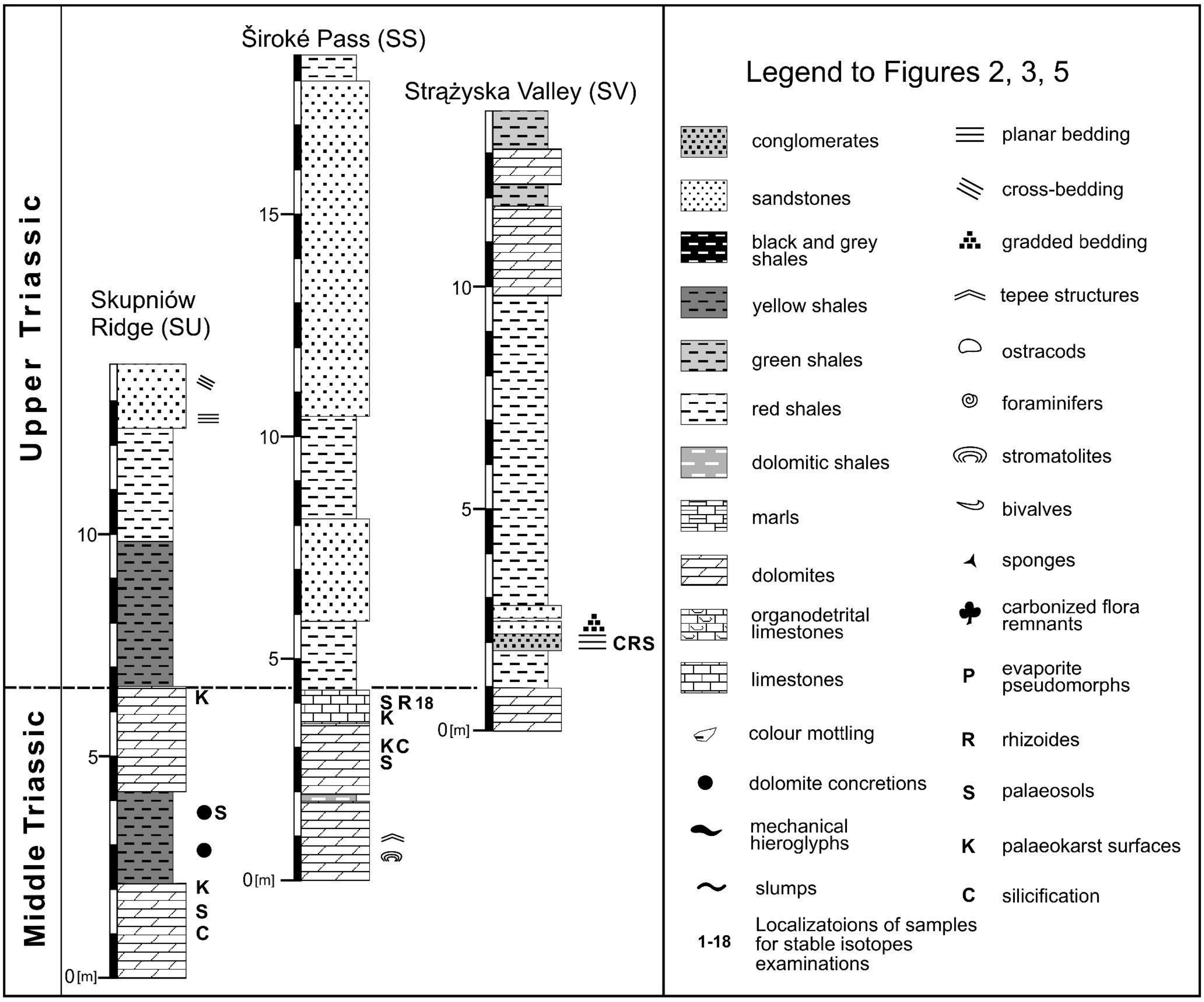

Fig. 3. Skupniów Ridge, Široké Pass and Strążyska Valley sections showing the transition between Middle Triassic carbonates and the Carpathian Keuper facies of the Krížna Nappe

genic fabrics overlie this complex (Fig. 10B, C). The carbonate palaeosols contain rhizoids and desiccation cracks (Fig. 10D). Terrigenic quartz and accessory minerals (zircon, titanite) are present. Upward, the clastic sediments replace the carbonates. The clastics commence with yellowish and red shales interbedded with white and pinkish coarse-grained, cross-stratified sandstones. The middle part of the section is poorly exposed, however, one may observe presence of sandstones up to several metres thick (see Fig. 7A) as well as conglomerates displaying gradded bedding. In the upper part of the section, in the Szeroka Bielska Pass, a transition to the Rhaetian (Fatra Formation) is visible. Thickness of the measured section is about 18.5 m.

Ždiar (ZS)

The section belongs to the Bujači Partial Nappe *sensu* Sokołowski (1948) (Jastrzębia Turnia – Palenica Partial Nappe *sensu* Bac-Moszaszwili & Lefeld, 1999 and Lefeld, 1999). The sediments crop out along the road from Ždiar to Poprad. This is the best outcrop of the Keuper in the Tatra Mts, but unfortunately, its contact with the Middle Triassic and the overlying, younger sediments is not visible. The section is subdivided into three parts (Fig. 5). The lower part (ZS I) crops out in the streambed of the Biela River. It begins with thick bedded dolomites (?uppermost Ladinian), intercalated with violet and grey shales. Toward the top, the dolomites are replaced by red and green shales with thin intercalations of sandstones and marls. The regoliths and pedogenic structures such as rhizoids are common (Fig. 6B). Total thickness of this part reaches 19.5 m. The middle part of the section (ZS II) is exposed in the road scarp. This section, over 42 m thick, is composed of variegated shales with beds of yellow-weathered dolomites and green sandstones. The beds are from a few centimetres to 1 m thick. Commonly they have erosive base featured by mechanical hieroglyphs.

Amalgamations of the sandstone layers are frequent (Fig. 7E). Thin layers often pinch out. Top of some sandstone beds is covered by red, muddy sediments with pedogenic fabrics. The dolomites from the upper part of the

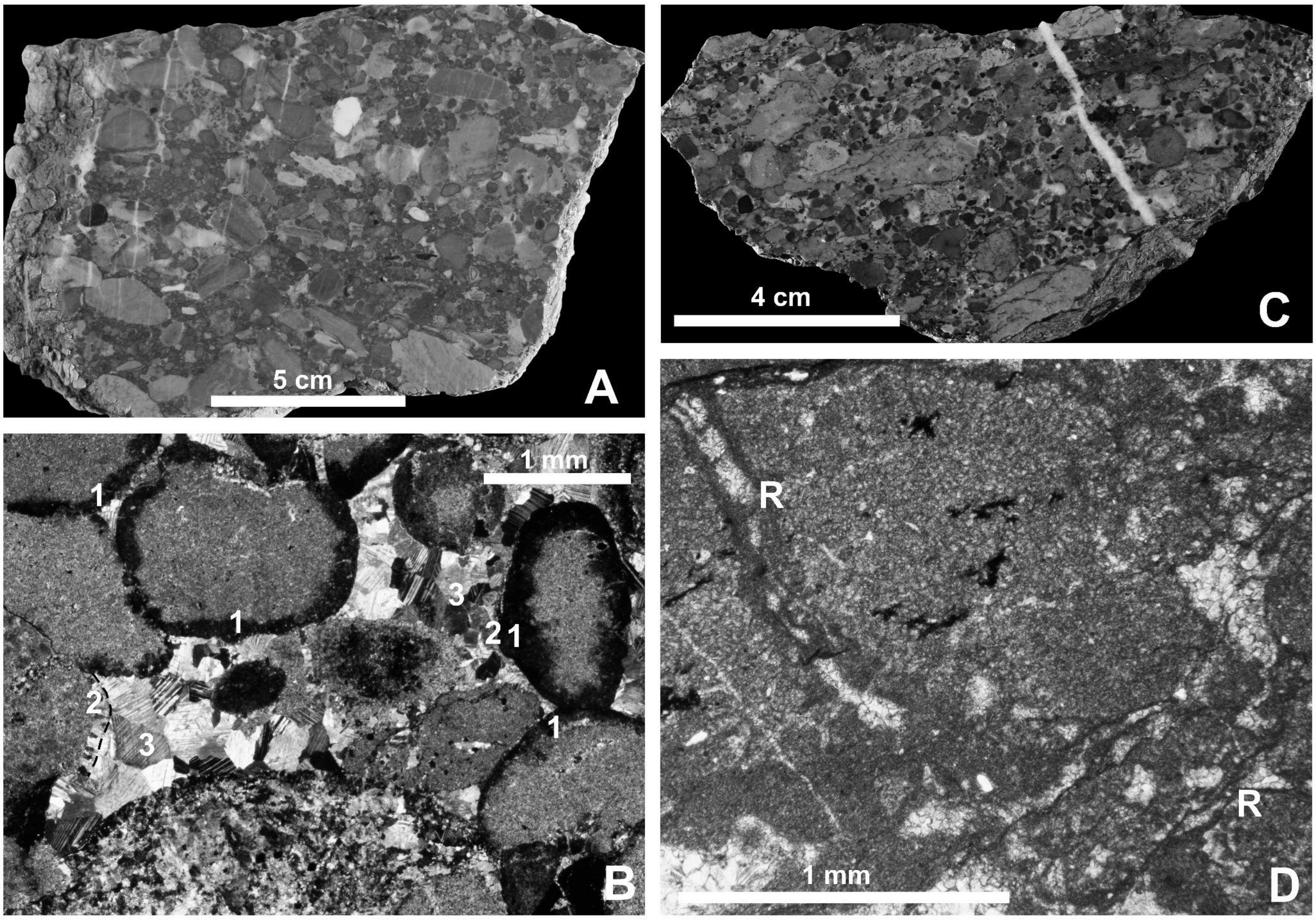

Fig. 4. Dolomitic conglomerates from the lower part of the Carpathian Keuper sections. **A.** Dolomite conglomerates from the SV section; **B.** Thin section of A (plane polarized light), note ferrigenous – rich rings around grains (1), and two generations of cement: early isopachous cement (2), later blocky sparite cement (3); **C.** Dolomite conglomerate from the SS section; **D.** Detail of C note the sparite filling voids (rhizoides – R)

section include rare fossils of ostracods, foraminifers and bivalves. Moreover, some mudstones comprise dolomitic concretions. The uppermost part of the section (ZS III) is exposed in a forest, ca 200 m to SE from the ZS II section. It begins with green shales, but mainly consists of thick dolomite layers with intercalations of dolomitic mudstones and shales. Red and grey cherts are ubiquitous in the dolomite beds (Fig. 11A). Thick dolomite beds display features of karstification. Surfaces of the beds are cracked and shales infill the cracks. The ZS III section is about 20.5 m thick.

Main lithofacies complexes of the Carpathian Keuper

Dolomitic conglomerates (A)

Red conglomerates with dolomites and chert grains are the typical sediments of the lowermost part of the Carpathian Keuper, although they have been found only in the Suchy Wierch and Havran units. Detailed petrographical description of the conglomerates from the Suchy Wierch unit was done by Turnau-Morawska (1953). She noted there common presence of iron hydroxides. The conglomerates display variable grains composition (Fig. 4A). Besides carbonate grains, detrital quartz is common. Small scale cross bedding is observed. In the lower part of the beds the conglomerates are grain-supported. The dolomite grains are angular and the conglomerates are poor in red clay material which becomes more common upward. The conglomerates are overlain by red shales. Most of the conglomerate pebbles display rim of iron hydroxides. In thin sections two generations of cement are visible within the conglomerate (Fig. 4B). The first one is the microsparitic cement which forms rims around grains. In the grain-supported parts, the second generation of cement is composed of dolosparitic crystals (see also Fig. 12D). There are evidences of silica mobilization, since the carbonate cement is partially replaced by microquartz, and silicrete are quite common. In the mud-supported deposits the sparite cements are often replaced by clay minerals. Similar conglomerates occur in the lower part of SS section in the Havran unit (Fig. 4C). They contain mostly angular dolomitic grains, cemented by sparite. Voids visible in thin sections are interpreted as rhizoids (Fig. 4D). The grains of both conglomerate types seem to derive from redeposited palaeosols. After the incorporation of Fe ions around the grains microsparite envelopes were formed at first in the vadose zone during the early diagenesis. Later the sparite and silica cements were formed.

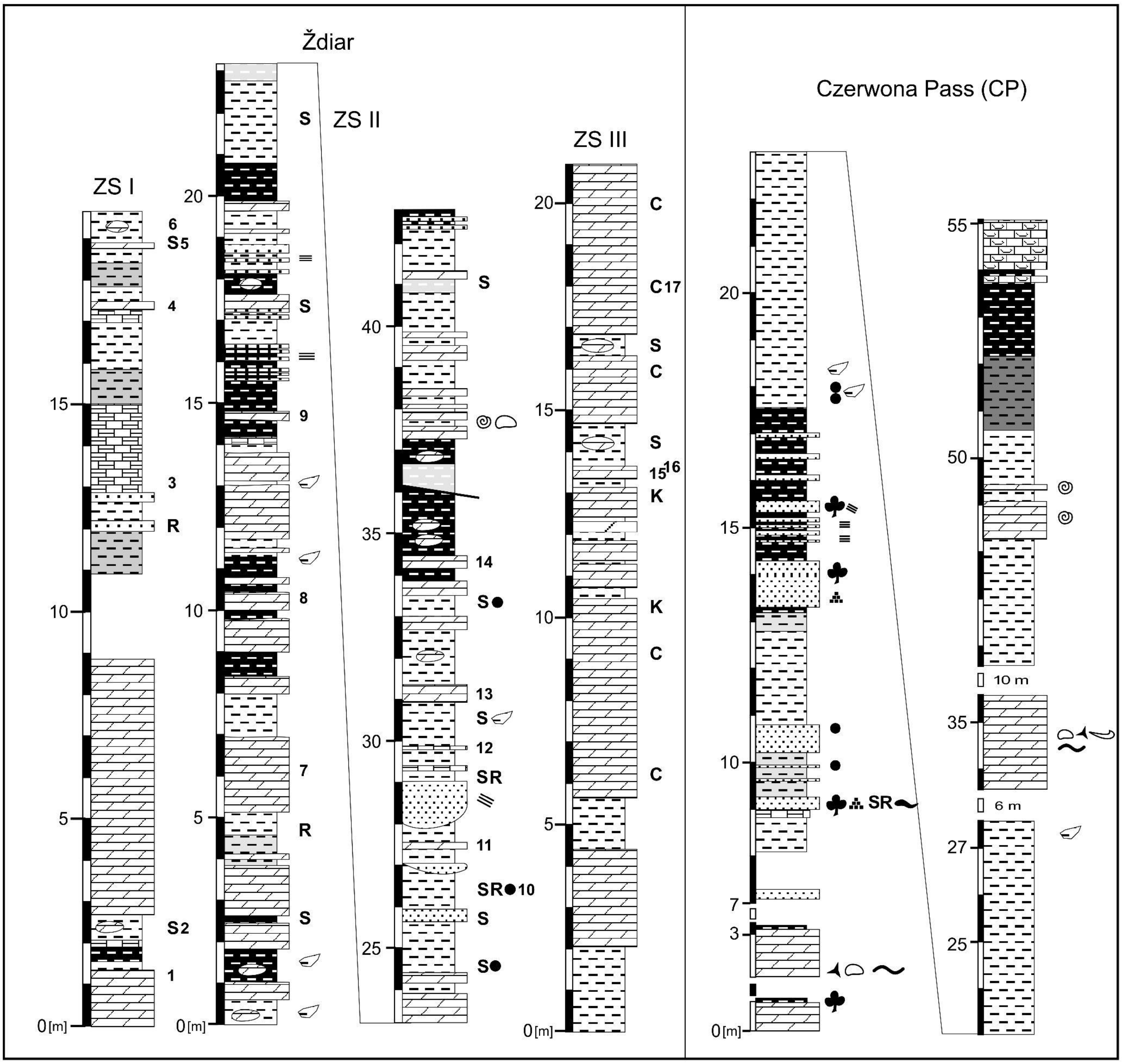

Fig. 5. ZS and CP sections of the Carpathian Keuper; see Fig. 3 for legend

Variegated shales with sandstones (B)

The dominating lithofacies of the Carpathian Keuper are red shales, which display also a palette of other colours: yellow, violet, green and grey (e.g., SU and ZS sections). The shales contain dolomicritic nodules from spherical to irregular in shape and up to several centimetres across. The nodules are commonly grouped in horizons. Red shales may build uniform thick complexes (up to 15 m), with sporadic gravels (Fig. 7C).

The sandstone beds from this lithofacies are up to 1 m thick. The sandstones are mostly green or yellowish in colour, with clayey or carbonate cements. Quartz and feldspars are main mineral components. Among clay minerals, kaolinite and smectite dominate, while titanite and zircon are most common among accessory minerals.

Thick-bedded sandstones and conglomerates (C)

In some sections of the Carpathian Keuper (SS, SU, LS, SV and in others, not described here) up to 10 m thick complexes of cross stratified coarse-grained sandstones and conglomerates occur. The conglomerates and sandstones are polymictic, with dominating quartz grains. They contain feldspars, tourmaline and zircon (Fig. 12G). Stratification is underlined by organic laminae or thin coal seams (Fig. 7B).

Variegated shales with dolomites (D)

In the LP, SU, ZS and LS sections, the shales contain intercalations of dolomite beds, which are up to 1 m thick. These are yellowish weathered dololutites, with common calcite veins and evaporite pseudomorphs. Some of the beds display erosive base, and pass gradually through dolomitic

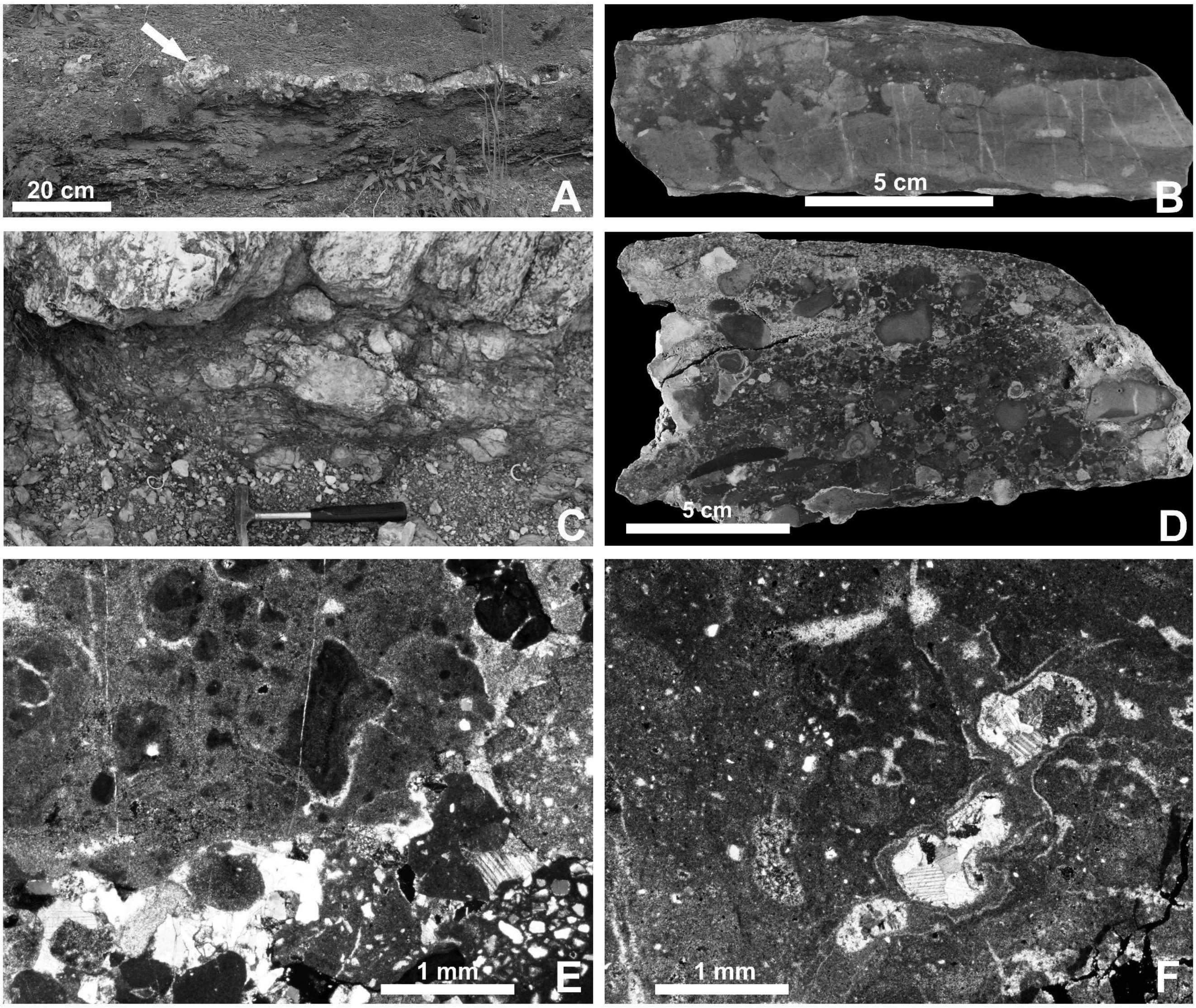

Fig. 6. Pedogenic fabrics of the Keuper sediments: **A.** Dolocrete layer from the ZS section; **B.** Polished slabs of the regolith horizon (ZS section). Note erosion of dolomite surfaces (light); **C.** Pedogenic concretions (SU section); **D.** Palaeosol (calcretes) (CP section); **E.** Thin section of the samples D – note the micritic nodules with some fine detrital grains and circum-granular cracks; **F.** Thin section of the samples D – note the sparite filling voids (rhizoides)

mudstones into mudstones. The dolomites from the SU section contain manganese concretions of about 100 μm in diameter (Fig. 12A). Silica nodules and veins are also very common (Fig. 12E). Dolomite concretions are ubiquitous in the intercalated shales (Fig. 6C). Most of dolomites from the ZS section are built of micrite and are cut by veins of saddle dolomite (Fig. 8D). Dolomites and shales from the upper part of the ZS section show a cyclic pattern (Fig. 13). Each cycle begins with thick (up to 40 cm) bed of dolomicrite, with marine fauna (foraminifers?, ostracods; Fig. 8A). The dolomite beds are thinning upwards and shales intercalations appear. Maximum thickness of the cycles reaches ca 5 m. The dolomites display sharp base, and pass gradually into shales. In the CP section, dolomites are rare, and show different facies. In coarser-grained intercalations, they comprise sponges, ostracods, foraminifers and bivalves. Dolomite beds contain ubiquitous traces of synsedimentary tectonics such as slumps and small faults (Fig. 9).

Thick-bedded dolomites with cherts (E)

In the Keuper clastics from the ZS and LS sections, thick complexes of light-grey, yellowish weathering dololutites occur. They intercalate shales with dolomitic concretions. Almost each thick dolomitic bed contains red or grey-coloured cherts. In thin sections one may recognize authigenic silica cements, including checkerboard chalcedony (see Murray, 1990), normal isopachous chalcedony, spherulitic chalcedony and megaquartz (Fig 11B–D). The isopachous texture indicates that the cements were formed within water-saturated pores (Murray, 1990). Partly crystallized chalcedony, crystals of calcite and quartz are visible under SEM (Fig. 12F). Small spherical bodies of dolomite

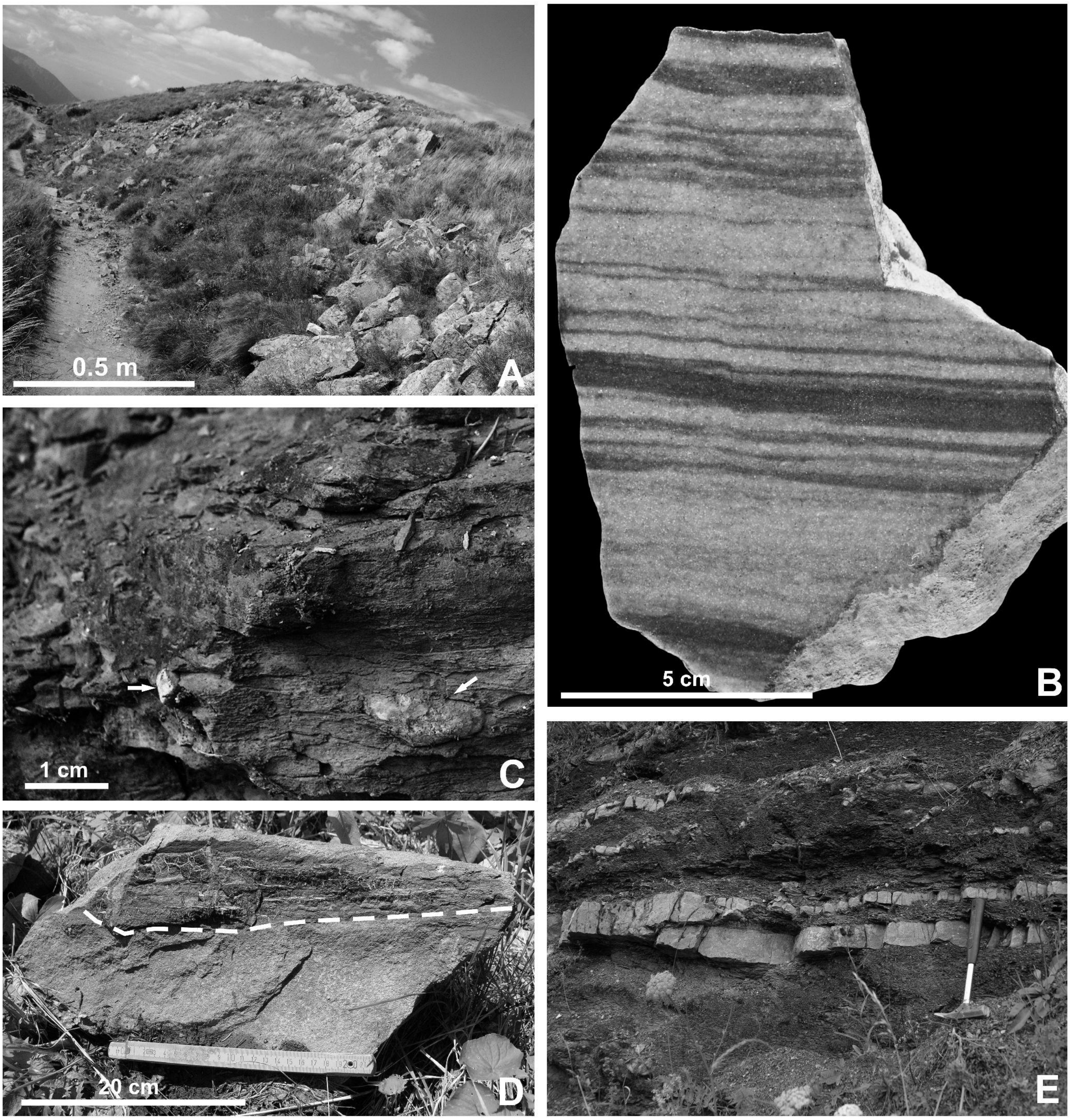

Fig. 7. Keuper sandstones: **A.** Outcrop of tick-bedded laminated sandstones (SS section); **B.** Planar-bedded sandstones with dark, organic matter rich laminae (SU section); **C.** Red shales with gravels (arrows; ZS section); **D.** Carbonized tree fragment in sandstones (CP section); **E.** Lateral thinning of sandstone beds (ZS section; hammer for scale)

of several micrometres in diameter are occasionally present on the chalcedony crystals. Within dolomites, crystals of celestite commonly occur (Fig. 12H).

The cherts occur only in thick, rubbled dolomite beds. They are absent in the well-stratified thin dolomite beds. Uppermost Ladinian dolomites from SU and SS sections also contain the cherts, although they are rare and smaller then these from ZS and LS sections. They partly replace the dolomite host rock. Under the SEM, well-crystallized, not corroded dolomites are still visible (Fig. 12B).

DISCUSSION

Sedimentary environments

During the Ladinian/Carnian transition a virtual change in sedimentary regime took place in the entire Fatricum Basin. It resulted from marine regression and climate changes (Szulc *et al.*, 2004; Rychliński & Szulc, 2005). Shallow water supratidal Middle Triassic carbonates became exposed and underwent karstification and erosion. These processes caused small stratigraphical gap between the Middle and

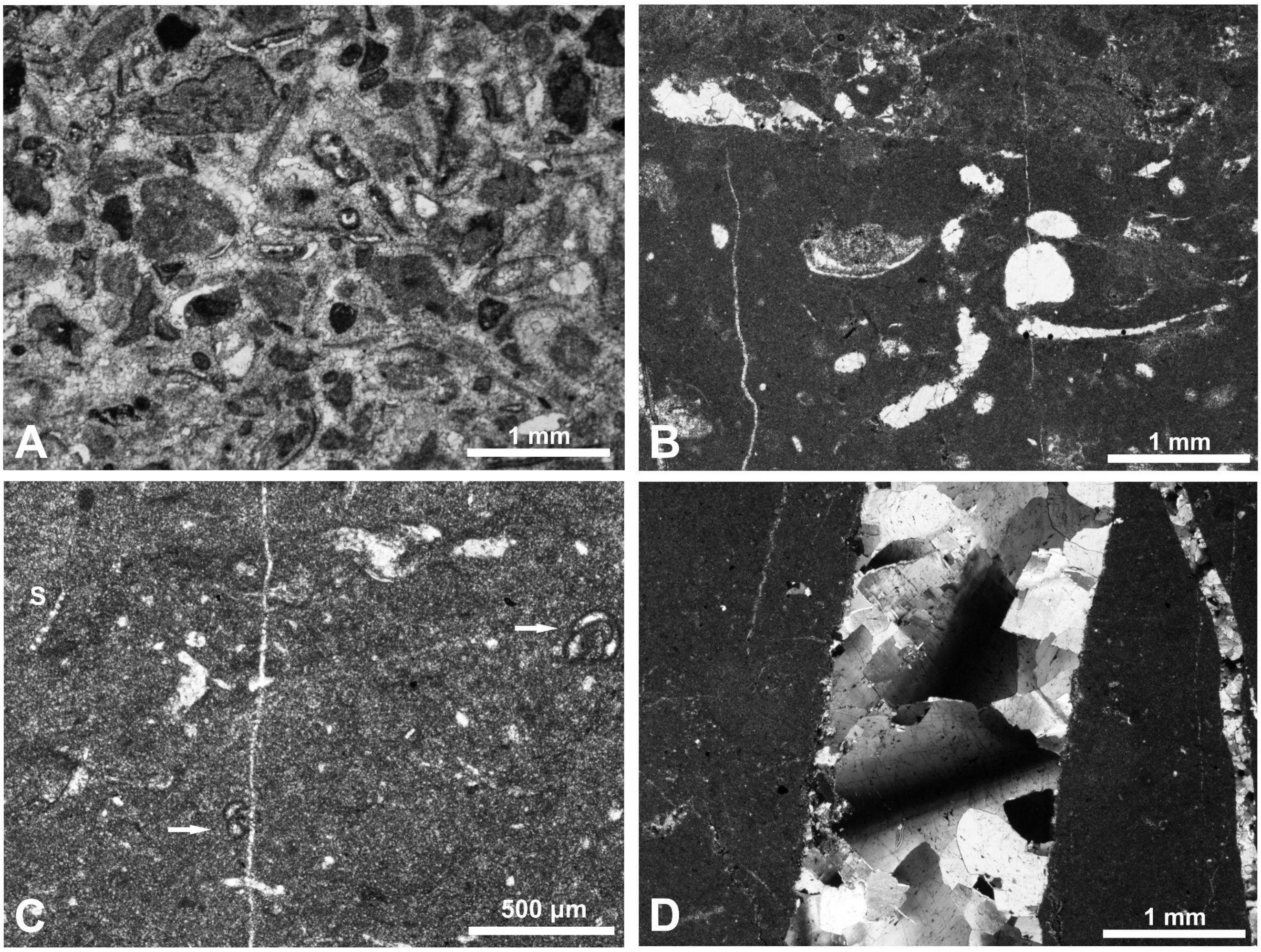

Fig. 8. Microfacies of the Keuper dolomites: **A.** Bioclasts from the cyclic dolomites (ZS section); **B.** Biomicrite with ostracods and bivalves (CP section); **C.** Biomicrite with foraminifers (arrows) and sponge spiculs (S) (CP section); **D.** Dolomicrite with saddle dolomite filling vein (ZS section)

Upper Triassic. Part of the emerged carbonate platform was eroded and carbonate conglomerates with ferruginous cements developed (Fig. 4). The skeletal grains were coated with reddish halo, characteristic for subaerial exposure (Allan & Matthews, 1982). In some other parts of the Fatricum Basin, calcretes with root structures developed (Fig. 10B–D). Karstification processes resulted in fissured surface of dolomites filled with green and yellow shales (for instance in the SU and SS sections).

Thickness of the Carpathian Keuper is variable, but probably it does not exceed 200 m.

After the episode of the emersion in the Fatricum Basin continental – shallow marine sedimentation prevailed. Clastic sediments represent mudflat and fluvial environments, while the carbonate beds represent sabkha environment.

Mudflat environment

Thick complexes of mudstones and sandstones representing continental deposits, formed in large mudflats. Thin sandstone intercalations represent mudflat channels. Presence of kaolinite in sandstones from the CP section indicates also a fluvial environment (Fig. 12C). Dolomite crusts covering the sandstone beds are interpreted as dolocretes. This type of clastic sedimentation is typical of mudflat and/or delta plains (McBride, 1974; Bridges & Leeder, 1976), but the presence of pedogenic fabrics indicates a mudflat. Some of the macroscopic features of the shales such as carbonate concretions or colour mottling are diagnostic of the palaeosols from the semi-arid climate zone (see Wanas & Abu El-Hassan, 2006). Thus, one may preclude that the red shales represent marine sediments as postulated by Turnau-Morawska (1953) and Al-Juboury and Durovič (1992), who ascribed illite and chlorite to marine environment although these minerals may also form in soils (Środoń, 1999; Wilson, 1999).

The variegated shales commonly contain dolomitic concretions and pedogenically changed dolomite beds. Moreover, there are ubiquitous dolomite layers, which laterally pass into nodular horizons (Fig. 6A). The rubbled structure and plant root structures point to pedogenic genesis of this type of concretions, which accords to geochemical investigations by Al-Juboury (2006), who regarded these concretions as early diagenetic in origin.

Fluvial environment

Thick complexes of quartz sandstones (up to 10 m thick) displaying small scale cross stratification and graded bedding, represent fluvial sediments. They occur in the SS and SU sections as well as in other parts of the Suchy Wierch Unit. The sandstones are oligomictic and consist mainly of quartz, with subordinate contribution of feldspars, micas and accessory minerals. The mineral maturity indicates a long transport. The presence of cross-bedding and absence of fine-grained intercalations as well as a lack of thick conglomerate beds indicate a meandering river system. The fluvial activity resulted from climate pluvialisation as suggested by rich plant detritus encompassed within the fluvial sediments.

Source of clastics

Source area for the Keuper clastics is not clear. Probably, the lower part of the red Keuper mudstones represents a *terra rossa* originated by weathering of the Middle Triassic carbonates under hot and semi-arid climate (Limanowski, 1903). The shales commonly contain detrital quartz and micas, whereas, the sandstones include also feldspars and accessory minerals like zircon, titanite and tourmaline, which indicates an external crystalline source rocks of the detritus (Turnau-Morawska, 1953). The present study does not bring definite data, whether the source area was the same as these of the Triassic siliciclastic sediments of the Northern Calcareous Alps and the Germanic Basin. Köppen and Carter (2000) suggested that the source area for Upper Triassic clastics in the NCA was the Fennoscandian Shield. They proposed a large system of braided rivers during Carnian times, which linked the Fennoscandia with the Tethys. Although thick fluvial sandstones are common in the Carpathian Keuper, the conglomerates, characteristic for braided rivers are almost absent. More detailed studies (for example analysis of heavy minerals) are needed to solve the problem of alimentation areas.

Sabkha environment

During marine ingressions the mudflat area was flooded and carbonate sedimentation developed. In the Carpathian Keuper the sabkha light-grey, yellow weathered dolomites are common. Evaporite pseudomorphs and poor fauna assemblages (ostracods and foraminifers) indicate that the dolomite sediments originated in hypersaline environment. The stromatolites and sponges (CP section) indicate litoral or supralitoral origin of dolomite, which confirms the observations of Al-Juboury and Durovič (1996). The bivalves occur only in calcarenites probably of tempestitic nature. Dolomites with foraminifers from the uppermost part of the CP section suggest sublitoral environment, while the overlying shales represent offshore sediments which are related to the Rhaetian transgression. Additional evidence of the hypersaline conditions is provided by the stable isotopes as discussed below.

Palaeogeographic data (Michalík, 1993, 1994) and facies development suggested that the Keuper dolomite beds from the Fatricum domain can be considered as equivalent of the Hauptdolomite facies, from other parts of the Carpathians and the Alps, for instance from Hronicum domain and from the Northern Calcareous Alps (e.g., Fruth & Scherreiks, 1984; Häusler *et al.*, 1993).

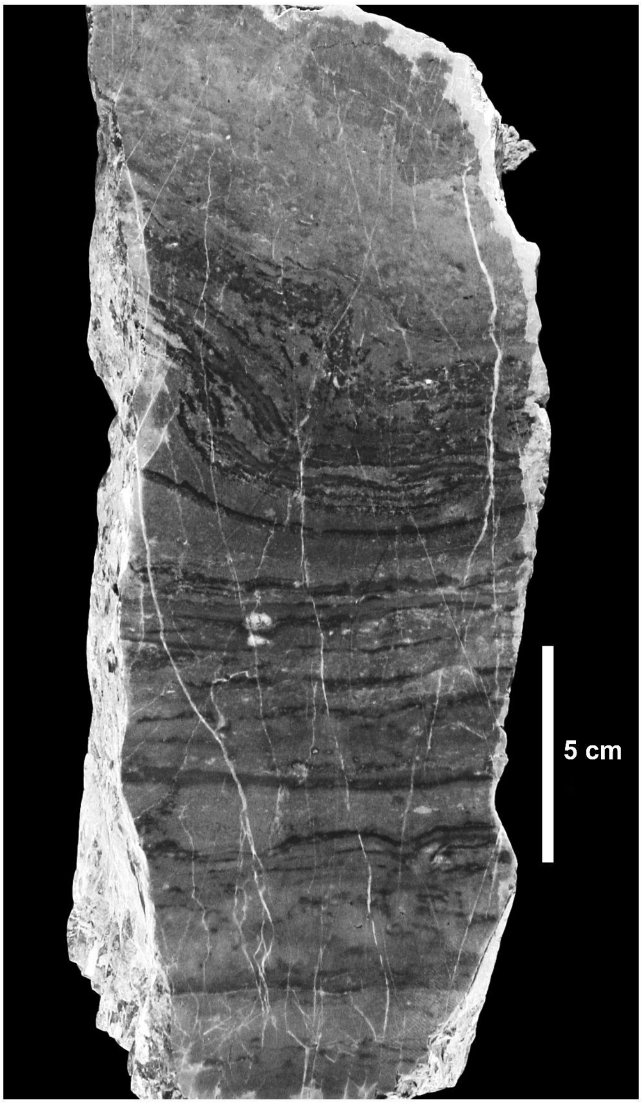

Fig. 9. Syndepositional deformation of the Keuper sponge-microbial laminites from the CP section

Main stages of the Keuper sedimentation

Although the described sections are not complete, the main trends of the Carpathian Keuper succession development can be recognized. Firstly, emersion and erosion of the Middle Triassic carbonate platform caused formation of the dolomitic conglomerates (lithofacies A). Next, the Fatricum domain was dominated by fluvial activity which affected deposition of thick sandstones and conglomerates of the lithofacies C and subordinate B. This stage is well documented in the SU and SS sections. After the fluvial deposition, alternate mudflat and sabkha sedimentation took place. The former resulted in the B and/or C lithofacies, while the latter caused deposition of dolomites and mudstones from

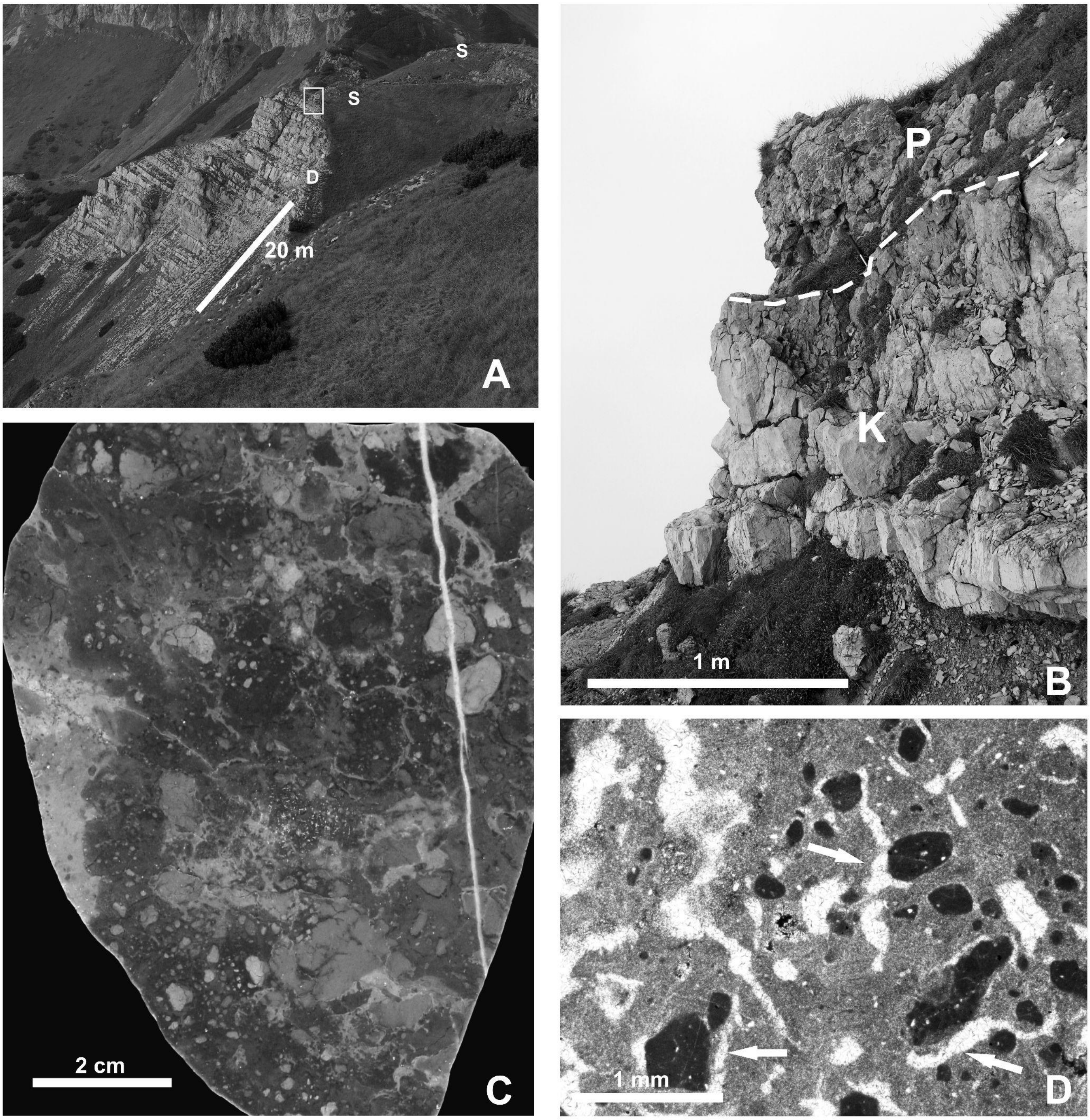

Fig. 10. The Szeroka Bielska Pass (SS) section: **A.** General view: D – dolomites of the uppermost Ladinian, S – sandstones of the Keuper. Rectangle shows the localization of Fig. 10B; **B.** Detail of the weathered uppermost Ladinian horizon: K – karstified dolomites with cherts, P – calcrete; **C.** Polished slab of the pedogenic limestones. Note the light dolomite pebbels in the limestone matrix; **D.** Thin section of C. Note sparite-filled voids – rhizoides and circumgranular cracks (arrows)

the lithofacies D and E. This stage is well documented in the ZS section. The mixed continental/shallow marine deposits are typical of the middle part of the Carpathian Keuper succession.

Lack of the B and C lithofacies in the upper part of the Keuper succession and presence of the D and E lithofacies (CP and LV sections) suggest that the basin was influenced by periodical marine ingressions during late Norian time, which climaxed with the Rhaetian transgression.

Palaeoclimate interpretation

According to sedimentary records of the Carpathian Keuper, during the late Triassic the palaeoclimatic conditions fluctuated. An insignificant climate humidisation is postulated after the drop of sea level and deposition of dolomitic conglomerates at the Middle/Late Triassic boundary. It is recorded by thick-bedded sandstones, and common karstification phenomena.

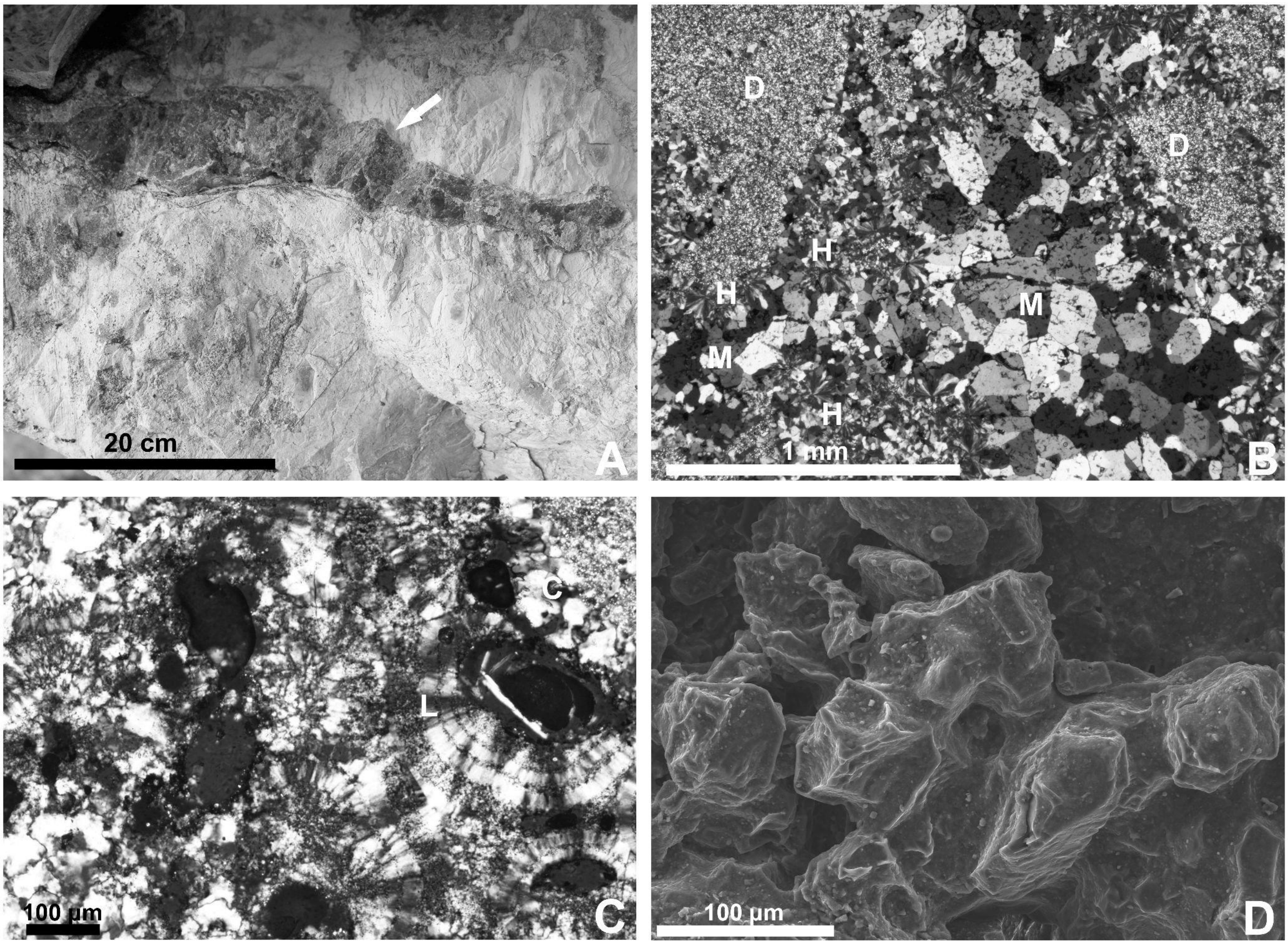

Fig. 11. Dolomites with silicification from the ZS section. **A.** Red chert (arrow) within the dolomites; **B.** Dolomite microsparite (D) replaced with rosettes of chalcedony (H) and megaquartz (M) – thin section, polarized light; **C.** Length-slow chalcedony (L) and checkerboard chalcedony (C) – thin section, polarized light; **D.** SEM view of megaquartz crystals

Later, during deposition of the middle part of the Keuper succession, the climate oscillated between wet and semi-arid. During the humid periods, thick sandstone beds were deposited. They are often accompanied by carbonized flora remnants and pedogenic fabrics. Equivalents of the wet Carpathian Keuper facies are also known from other parts of Western Tethys domain (Szulc, 2000). During the periods of semi-arid climate, thick complexes of red clastics with horizons of pedogenic concretions were deposited. The concretions along with silicretes are typical of the whole Keuper succession and indicative of the semi-arid climate (Summerfield, 1983; Warren, 1983).

During the sea ingressions, the semi-arid condition caused high evaporation and deposition of dolomites with evaporite pseudomorphs. Semi-arid conditions can be postulated as dominant palaeoclimatic feature in the Fatricum domain during Carnian–Norian times, with subordinate significance of the humid periods. These humid intervals resulted from the influence of monsoonal climate, which existed at the Pangea megacontinent during Permian and Triassic time (Mutti & Weissert, 1995).

Silicification of sabkha dolomites

Thick dolomites from the ZS and LP sections, interpreted as sabkha deposits, contain red and grey cherts. In thin sections one may recognize anhedral crystals of megaquartz (over 20 µm) and microquartz, chalcedony, quartzine and lutectite. Folk and Pittman (1971) suggest that quartzine and lutectite are indicators of sulphate-rich environments. The source of silica for the Carpathian Keuper is not clear. Mišík (1995a, b) postulated that silica of microquartz and authigenic quartz crystals derived from radiolarian tests and sponge spicules and/or from siliciclastic deposits intercalated within carbonates. However, in the silicified dolomite no siliceous microfossils have been found. Therefore, the most probable source of silica is the siliciclastic deposits. Authigenic quartz crystals (euhedral macroquartz) were found in pores of dolomites from the ZS section and from veins cutting dolomites of the CP section and within foraminifers shells. Moreover, the dolomites are rich in corroded detrital quartz grains. The dissolved silica could migrate during the diagenesis and re-precipitated in

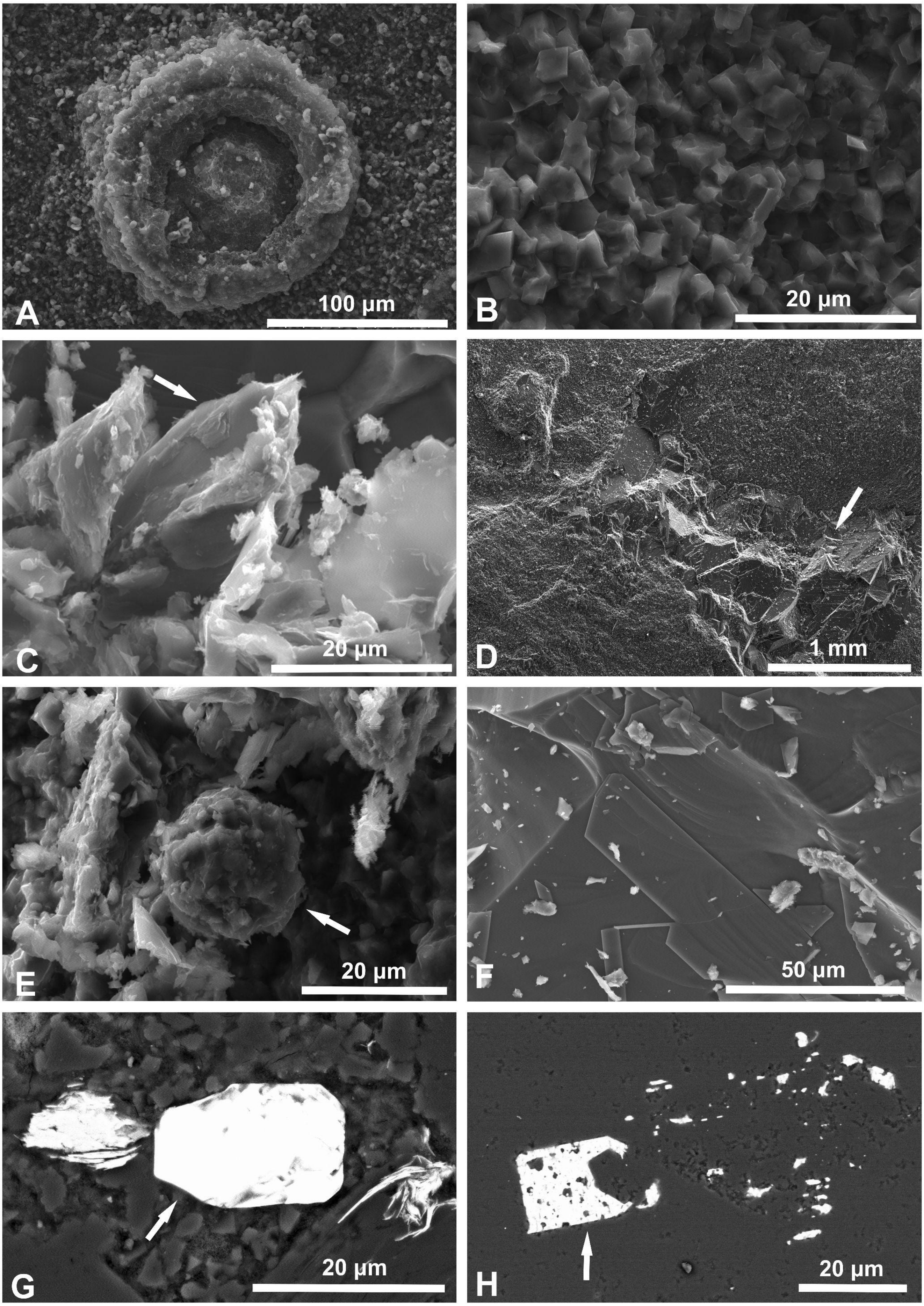
100 µm
A
20 µm
B
20 µm
C
1 mm
D
20 µm
E
50 µm
F
20 µm
G
20 µm
H

Fig. 12. The SEM images of the Carpathian Keuper: **A.** Manganese concretions from karstified dolomites (SU section); **B.** Dolomite crystals (SU section); **C.** Kaolinite crystals (arrow) from palaeosols (CP section); **D.** Sparite cement (arrow) in carbonate conglomerates (SV section); **E.** Silica nodule (arrow) from karstified dolomites, Ladinian/Carnian boundary (SU section); **F.** Quartz crystal from silcretes (polished surface; CP section); **G.** Zircon (arrow) from sandstones of the ZS section (polished surface); **H.** Celestite crystal (arrow) from dolomites with silicifications (polished surface; ZS section)

the form of chert concretions. The presence of celestite crystals and evaporite pseudomorphs (birds-eye type – Shinn, 1968) within the dolomites with cherts is another indicator for sabkha origin of the Keuper dolostones.

Variability of sedimentary environments

The Carpathian Keuper succession displays intense facies variability. This phenomenon along with syndepositional faults, dilatation fractures, sigmoidal deformations and slumps indicate that the Fatricum domain was a tectonically mobile area during late Triassic. The synsedimentary tectonics resulted in differentiated topography of the basin. Probably the basin was divided into several tectonic blocks already in Middle Triassic (Mišík, 1968, 1972; Michalík *et al.*, 1992; Michalík, 1997; Szulc *et al.*, 2004; Rychliński & Szulc, 2005). During Carnian and Norian the uplifted blocks were eroded, while the downfaulted mudflat depressions were flooded by episodic marine ingressions when the extremely shallow water dolomites formed.

Stable isotopes examination

Interpretations of $\delta^{13}C$ and $\delta^{18}O$ curves allow to draw conclusions about sedimentary environments and diagenetic history of the studied rocks. Because similar isotopic

Table 1

The isotopic composition of the analyzed samples (for localization of samples see Figs 3 and 5)

Samples	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)
1	–2.7	–2.1
2	–3.5	–4.7
3	–3.9	–4.6
4	–4.0	–2.4
5	–5.0	–4.7
6	–4.5	–3.7
7	–2.6	–3.8
8	–3.0	–3.8
9	–4.9	–2.7
10	–2.8	–4.4
11	–7.2	–4.7
12	–7.9	–3.3
13	–7.2	–4.7
14	–2.8	–4.4
15	–6.7	–3.2
16	–0.7	2.0
17	–3.7	–5.3
18	–10.6	–6.6

Fig. 13. Cyclic pattern in dolomites and shales from the ZS section. Note upward thinning dolomite layers to the cycle tops. S – sandstones

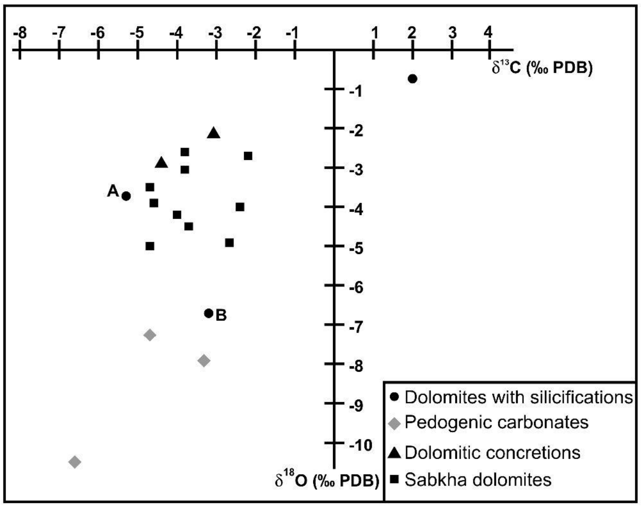

Fig. 14. Cross-plot of $\delta^{13}C$ versus $\delta^{18}O$ for the Carpathian Keuper carbonates

trends may be sometimes interpreted in different ways, the interpretations have to take into considerations also the general sedimentary context of the studied rocks. From 18 samples examined in terms of their stable isotope signals only one shows positive values (Table 1; Fig.14). In the other 17 samples the $\delta^{13}C$ ranges from –2.2‰ to –6.6‰ while $\delta^{18}O$ ranges from –2.1‰ to –10.5‰. Negative values of oxygen and carbon isotopes are noted in the pedogenic carbonates. The most negative value of $\delta^{13}C$ and $\delta^{18}O$ characterises the pedogenic calcrete horizon overlying the karstified dolomites of the uppermost Ladinian age in the SS section. Negative values of $\delta^{13}C$ are typical of subaerially exposed carbonates which underwent meteoric diagenesis (Allan & Matthews, 1982). Similar isotope signals have been also reported by El-Sayed *et al.* (1991) for the Cenozoic calcretes from Kuwait.

Two samples representing dolomite concretions from the shales show negative signals of $\delta^{13}C$ (–3.1 and –4.4) and $\delta^{18}O$ (–2.1 and –2.8) with low variability of the values. Isotopic composition of dolomites with cherts is variable. The sample marked as A (see Fig. 14) comes from sabkha dolomites from ZS section, while the sample B comes from karstified horizons of the sabkha dolomites.

The samples from the sabkha dolomite show negative values of $\delta^{13}C$ ranging from –2.2 to –4.7 while $\delta^{18}O$ ranges from –2.6 to –5.0. Similar values have been reported by Chafetz *et al.* (1999) for sabkha dolomites from the Arabian Gulf. As the main reason for the negative isotopes trends, they suggest bacterial sulfate reduction rather than influence of meteoric water. However, Allan and Matthews (1982) show that the negative trend for the carbonates is associated with early meteoric diagenesis and is a function of depth below paleosurface. Most negative values are nearby the surface and they grow downsection. Similar trend has been also found in the present case where dolomitic beds, displaying negative isotopic signals are overlain directly by palaeosols so the obtained isotopic signals can be considered as a result of meteoric diagenesis.

The most positive values (+2 and –0.7 of $\delta^{13}C$ and $\delta^{18}O$ respectively) were obtained from the late diagenetic calcite veins cutting the chert-bearing dolomites from the uppermost part of the ZS section.

Cyclicity of the Keuper sedimentation

Some sections of the Carpathian Keuper display quite regular cyclicity. It is expressed by alternations of clastic deposits (mudstones and sandstones) and carbonates. The cyclicity is well visible in the Ždiar section where some shallowing upward cycles have been observed. Each cycle begins with a thick dolomite bed, containing ostracods and foraminifers. The bases of the dolomite beds are sharp. The dolomites are replaced gradually by variegated shales. This type of cyclicity has been reported from other parts of the Western Tethys and may be ascribed to sea level fluctuations (Bechstädt & Schweizer, 1991; Haas, 1994). Thickness of the cycles (maximally up to 5 m) point to high frequency cycles. It is difficult to determinate the main cause of the cyclicity, however eustatic changes of sea level with subordinate importance of climate changes are the probably cause. The cyclicity of the Carpathian Keuper clastic sediments in the lower part of the succession was, in turn, the result of climate changes.

CONCLUSIONS

1. The Carnian–Norian Carpathian Keuper sediments from the Tatra Mts consist of mixed carbonate-clastic deposits of various origin.
2. After regression at the end of Ladinian, sedimentary regime changed. The middle Triassic carbonate platform was exposed and pedogenesis as well as karstification processes developed. Carbonate conglomerates from the lower part of the Keuper succession point to weathering and erosion phenomena.
3. The dominating thick complexes of variegated shales with intercalations of green and pink sandstones represent a mudflat environment. Thin sandstone beds were deposited in mudflat channels. Thick cross-stratified sandstones with carbonized flora remnants represent meandering river systems developed during intervals of climate pluvialisation.
4. Dolomitic concretions within shales are interpreted as pedogenic and confirm the mudflat environment of the shales.
5. During marine ingressions the mudflat was flooded and dolomite beds formed. According to sedimentary structures, palaeontological and stable isotopic data, the dolomites formed under hypersaline conditions.
6. The Carpathian Keuper sediments were deposited under semi-arid climate conditions with periods of monsoonal circulation marked by coal-bearing sandstones.
7. The cyclic pattern of the Carpathian Keuper sediments seems to be an effect of both climate changes and sea level fluctuations. In the lower part of the Keuper succession, where the sandstones and shales dominate, the cycles resulted from climate changes. Dolomite/clastic cycles from the upper part of the succession were probably generated by sea level fluctuations.
8. Intensive facies variability within the Carpathian Keuper is the consequence of synsedimentary tectonic movement affecting the Fatricum basin during Carnian–Norian times.

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