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PERMIAN TO TRIASSIC PALEOKARST OF THE ŚWIĘTOKRZYSKIE (HOLY CROSS) MTS, CENTRAL POLAND

Permsko-triasowy kras kopalny Gór Świętokrzyskich, Polska środkowa

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Abstract: This paper presents classification of the Permian and Triassic paleokarst forms in the Świętokrzyskie Mts, systematic description of the groups of forms and their fillings as well as conclusions concerning environmental conditions of their development. Four groups were distinguished among paleokarst forms developed before the deposition of the Buntsandstein whereas five ones developed during the Buntsandstein deposition (proceeding diachronically) and/or the Middle Triassic time. The Permian-Triassic paleokarst was conditioned by the Variscan tectonic movements and uplift as well as subsequent formation of the Danish-Polish Trough. The Permian karst developed in the area of mountainous morphology and were often connected with hydrothermal processes. The Triassic karst formed due to tectonic activity stimulating morphological rejuvenation of the region. Wide and low passages representing one of the Triassic paleokarst group presumably formed in fresh and sea waters mixing zone.

Key words: paleokarst, Permian, Triassic, paleogeography, Świętokrzyskie (Holy Cross) Mts

Treść: Artykuł prezentuje klasyfikację permskich i triasowych form paleokrasowych w Górach Świętokrzyskich, systematyczny opis poszczególnych typów tych form oraz ich wypełnień, jak również wnioski dotyczące warunków ich rozwoju. Wyróżniono cztery typy form pseudokrasowych powstałych przed sedymentacją osadów pstrego piaskowca oraz pięć typów tworzących się w trakcie sedymentacji pstrego piaskowca (następującej diachronicznie) oraz/lub środkowego triasu. Permsko-triasowy kras kopalny był warunkowany waryscyjskimi ruchami tektonicznymi oraz wyniesieniem regionu, a następnie tworzeniem się niecki duńsko-polskiej. Kras permski rozwijał się na obszarze o górskiej rzeźbie i był często związany z procesami hydrotermalnymi. Kras triasowy powstał w rezultacie aktywności tektonicznej powodującej odnowienie rzeźby regionu. Szerokie i niskie kanały reprezentujące jedną z generacji krasu triasowego utworzyły się prawdopodobnie w strefie mieszania się wód słodkich i słonych.

Słowa kluczowe: kras kopalny, perm, trias, paleogeografia, Góry Świętokrzyskie

INTRODUCTION

Karst forms developed in subaerial environments represent specific “traps”, in which records of geomorphological evolution of land areas can be conserved. Although deciphering such records is usually difficult, it often offers the only possibility for reconstruction of terrestial periods of the geologic history (Głazek 1973, Bosak 1997). Terrestial periods represent *ca* 30% of the time of the Phanerozoic history of the Świętokrzyskie Mts. Occurrence of thick sequence of the Devonian carbonates caused that the periods of subaerial exposure of the Paleozoic rocks since the Middle Devonian could be marked by development of karst forms.

Karst forms in the Paleozoic core of the Świętokrzyskie Mts developed during three principal karst periods:

1) Middle-Upper Devonian, when karst was connected with local and short emergences of freshly deposited carbonates (Szulczewski *et al*. 1996);
2) Late Carboniferous(?)-Permian to Triassic period;
3) Cenozoic period, started with the Late Cretaceous-Early Paleogene uplifting (Urban 2002).

Paleokarst forms which developed in the Devonian carbonates during the Permian--Triassic and Cenozoic terrestial periods represent interregional karst (*sensu* Choquette & James 1988). The recognition and interpretation of paleokarst forms are the main topics of the study. This paper presents classification of the Permian and Triassic paleokarst forms in the Świętokrzyskie Mts, systematic description of the groups of forms and their fillings and conclusions concerning environmental conditions of their development. On the base of detailed description of paleokarst groups and their succesion, wider suggestions about geological and morhological (paleogeographical) evolution of the region during the Permian and Triassic time are presented.

GEOLOGICAL SETTING

The Świętokrzyskie Mts region consists of two structural units:

1) the Paleozoic core tectonically framed during the Caledonian and Variscan orogenic cycles and modified by the Alpine tectogenesis (Fig. 1),
2) the Permian-Mesozoic platform encircling the Paleozoic core and tectonically modified during the Alpine movements.

Within the Permian-Mesozoic platform several tectonic windows of uplifted blocks of the older Paleozoic rocks (with paleokarst forms) are located. Two tectonic and facies subunits are distinguished in the region: the northern Łysogóry subregion and southern Kielce subregion (Kutek & Głazek 1972).

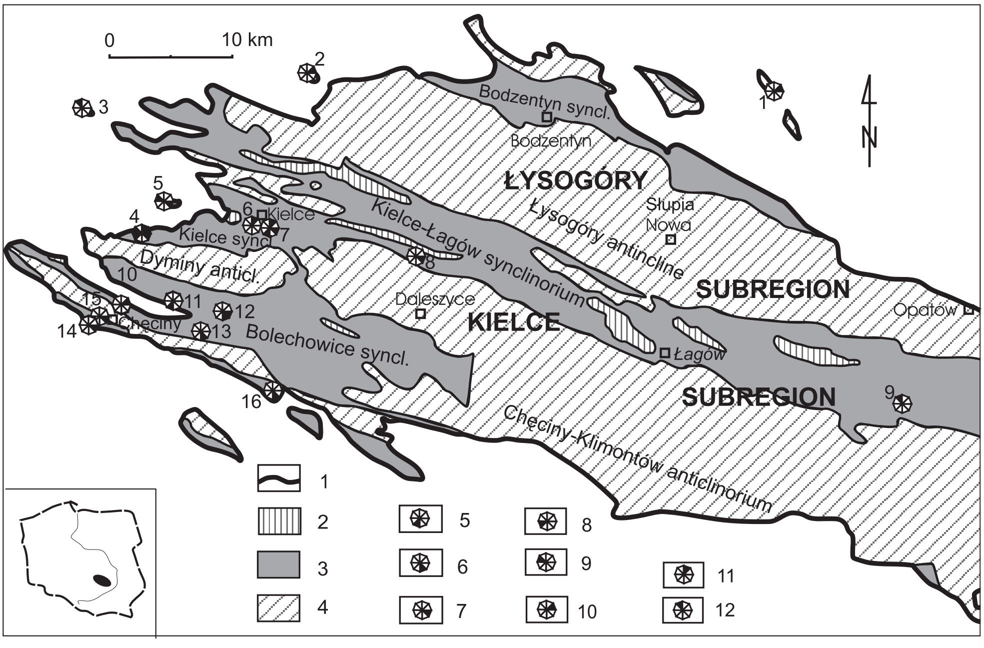


Fig. 1. Permian-Triassic karst in carbonates in the Świętokrzyskie Mts. Explanations of symbols: 1–4 – outcrops of geological units: 1 – margin of the Paleozoic core outcrop, 2 – Carboniferous (siltstones, locally marls and limestones), 3 – Middle and Upper Devonian (limestones, dolomites, marls, in the Łysogóry subregion also siltstones and sandstones), 4 – Older Paleozoic and Lower Devonian (sandstones, siltstones, shales, locally marls and limestones); 5–12 – sites of the Permian-Triassic paleokarst and other denudational forms: 5 – zones of pre-Triassic surface karstification, erosion and gravitational mass movements (I), 6 – karstified tectonic fissures filled with hydrothermal calcite and clastic carbonates (II), 7 – subsurface karst forms and sinkholes filled with clastic or chemical carbonates (III and IV), 8 – subsurface karst forms filled mainly with sandy limestones (V), 9 – "large lenses" (VI), 10 – surface karst and other denudational forms contemporaneous with the deposition of the Lower Buntsandstein (VII), 11 – forms filled with the Buntsandstein sandstones – mainly "clastic dykes" (VIII), 12 – karst forms filled with carbonates of the Röt or Muschelkalk (IX). Numbers of sites: 1 – Doły Opacie, 2 – Zachełmie, 3 – Strawczyn, 4 – Jaworznia, 5 – Szczukowskie Górki, 6 – Kadzielnia, 7 – Wietrznia, 8 – Józefka (Górno), 9 – Wymysłów, 10 – Zelejowa, 11 – Zgórsko, 12 – Trzuskawica-Kowala and Trzuskawica Nowa, 13 – Kowala-Nowiny, 14 – Rzepka-Korzecko, 15 – Rzepka-Chęciny, 16 – Łabędziów

Fig. 1. Permsko-triasowy kras w skałach węglanowych Gór Świętokrzyskich. Objaśnienia symboli: 1–4 – wychodnie jednostek geologicznych: 1 – granica wychodni trzonu paleozoicznego, 2 – karbon (mułowce, lokalnie margle i wapienie), 3 – środkowy i górny dewon (wapienie, dolomity, margle, w subregionie łysogórskim także mułowce i piaskowce); 5–12 – stanowiska permsko-triasowego paleokrasu oraz innych form denudacyjnych: 5 – strefy przedtriasowego krasowienia, erozji oraz grawitacyjnych ruchów masowych (I), 6 – skrasowiałe szczeliny tektoniczne wypełnione kalcytem hydrotermalnym i klastycznymi skałami węglanowymi (II), 7 – podpowierzchniowe formy krasowe oraz leje krasowe wypełnione klastycznymi lub chemicznymi skałami węglanowymi (III i IV), 8 – podpowierzchniowe formy krasowe wypełnione głównie wapieniami piaszczystymi (V), 9 – „wielkie soczewy" (VI), 10 – powierzchniowe formy krasowe oraz inne formy denudacyjne współczesne z depozycją osadów dolnego pstrego piaskowca (VII), 11 – formy wypełnione piaskowcami pstrego piaskowca – głównie „żyły klastyczne" (VIII), 12 – formy krasowe wypełnione skałami węglanowymi retu lub wapienia muszlowego (IX). Numeracja stanowisk – patrz objaśnienia w języku angielskim

Carbonate rocks

The Devonian carbonates represent principal karst rocks in both subregions of the Świętokrzyskie Mts. In the Kielce subregion, the sequence of the Middle and Upper Devonian dolomites and limestones is several hundreds meters thick. Stromatoporoid-coral limestones and dolomites of the Kowala Formation (Givetian-Frasnian) and Eifelian dolomites (Wojciechowice Formation) represent the most extensively occurring Devonian carbonates. In peripherial zones they were accompanied by biodetrital carbonates (not included in the Kowala Fm). In the Łysogóry area, the occurrence of karstified rocks is restricted to the Eifelian and lower Givetian dolomites up to 300 m thick. The Eifelian dolomites are bedded with inserts of marls in the lower part. The limestones and dolomites of the Kowala Fm are generally micritic with more or less abundant organic elements. They are usually thick-bedded, locally massive or thin-bedded. Dolomite/limestone boundary is stratigraphically discordant extending from Givetian to Frasnian. The limestones and dolomites of the Kowala Fm are generally high-grade carbonates (Rubinowski *et al*. 1986, Szulczewski 1995a, Szulczewski *et al*. 1996).

Variscan and early post-Variscan evolution

The Variscan tectonic movements significantly influenced geological structure of the Paleozoic core of the Świętokrzyskie Mts. The movements caused folding and uplift resulting in a lack of the Upper Carboniferous sediments. Occurrence of the Lower Permian rocks is also not evident (Kutek & Głazek 1972, Głazek 1989, Szulczewski 1995a).

During the Late Permian time the region was situated in the marginal, eastern part of the Central European Zechstein basin (Wagner 1994). According to one model, the central part of the region formed large mountainous peninsula encircled on the west, south and north by sea during each of Zechstein transgressions. The largest extend of marine sediments is connected with the first transgression (PZ1). At that time, peninsula margins were similar to limits of the current outcrop of the Paleozoic core (Kowalczewski & Rup 1989). According to another model, the Paleozoic core was dissected into the set of tectonic blocks (horsts), which formed several mountainous islands surrounded by PZ1 sea (Kutek & Głazek 1972).

Zechstein sediments occurring along margins of the Paleozoic outcrops of the Świętokrzyskie Mts form relatively thin blankets of clastics and carbonates of PZ1, locally evaporates of PZ2 and fluvio-lacustrine sandstones, siltstones and clays of the last cycle called PZt. Poorly sorted conglomerates, composed of local material are the most characteristic Zechstein sediments occurring close to the margins of the Paleozoic core. Climate of the Late Permian was hot and arid with more humid periods (Kowalczewski & Rup 1989, Kuleta & Fijałkowska 1995, Zbroja *et al*. 1998, Kuleta & Zbroja 2006).

The Zechstein/Buntsandstein boundary is identified with marine ingression, which covered Zechstein basin and reached the northwestern foreland of the Świętokrzyskie Mts (Pieńkowski 1991). The sediments of ingression are situated in the profile close to paleomagnetic and paleofloristically determined Permian/Triassic boundary (Kuleta & Fijałkowska 1995, Nawrocki *et al*. 1993, 2003, Nawrocki 1997). According to these data the Zechstein/Buntsandstein boundary is assumed in this paper as almost identical with Permian/Trassic one, disregarding some questions on this topic (e.g. Ptaszyński & Niedźwiedzki 2006). Lithologically the beginning of the Buntsandstein sedimentation has been principally related to the appearance of allogenic quartz pebbles in the monotonous sequence of siliciclastics (Senkowiczowa 1970), although other features (geochemic, physic – see Kuleta & Zbroja 2006) are also quoted as criteria of distinguishing the Zechstein from Buntsandstein sequences.

The Early Triassic subsidence of the north-western foreland of the Paleozoic core, related to initial phase of the Danish-Polish Through development (Hakenberg & Świdrowska 1998), was compensated by mainly terrestial deposition of the Buntsandstein. The Lower and Middle Buntsandstein sequence consists of sandstones interbedded with conglomerates, siltstones and clays, which thickness generally increases toward NW. Sandstones, mudstones and conglomerates of the lowermost Buntsandstein formations: Siodła Fm (complex A0), Jaworzna Fm (A) and Szczukowice Fm (A1), which overlay the Zechstein or directly the Variscan structures, were deposited in swamps, lakes and marginal zone of the marine ingression. The deposited material was mainly transported from the area situated southeast and south of the central part of the Świętokrzyskie Mts. region. In the western and northern part of the region the Buntsandstein sequence is more or less complete thickening to the NW, whereas occurrence of the Buntsandstein in the eastern part of the Paleozoic core is not proved. Climate of the Early Triassic time was tropical with more humid and extremely dry periods (Senkowiczowa 1970, Fijałkowska 1994, Fijałkowska & Kuleta 1994, Kuleta & Zbroja 2006).

The Łukowa beds of the lower Muschelkalk (Anisian – Trammer 1975, Fijałkowska-Mader 1999) are the youngest Triassic unit in the western part of the region, which sedimentation directly on the Paleozoic core has been documented (Senkowiczowa 1970). During the Middle and Late Triassic time subsidence of the region was relatively slow and periodically even interrupted, but no trace of the Late Triassic denudation of the Paleozoic core have been found. The Jurassic and Cretaceous were the periods of sedimentation in the continuously depressed area (Kutek & Głazek 1972, Hakenberg & Świdrowska 1998).

Variscan period of the Świętokrzyskie Mts evolution was expressed by several phases of hydrothermal, low-temperature mineralization represented by veins of coarse-crystalline calcite, which occur in the Devonian carbonates.

Rubinowski (1971) described two main phases of the calcite veins development:

1) Variscan formation of calcite veins and calcite-limestone/dolomite breccias called “różanka” (“pinkish calcite”),
2) post-Variscan veins of “honey-coloured calcite” with barite and galena.

Migaszewski *et al*. (1996) distinguished four phases of mineralization: phase A related to the Variscan orogeny (Late Carboniferous), phase B – older post-Variscan (probably Late Carboniferous-Early Permian) and phases C and D – younger post-Variscan (likely Late Permian and Early Triassic). Some younger generations (of D phase) are characterised by occurrence of barite and galena and occasionally form impregnations in the Lower Buntsandstein. Phases C and D were supposed by Migaszewski *et al*. (1996) to be connected with karstification, but the example shown by them (in Rzepka quarry) does not confirm this opinion (Wierzbowski 1997).

PREVIOUS INVESTIGATIONS OF THE PERMIAN-TRIASSIC PALEOKARST

Hundreds of the paleokarst sites have been registered in numerous outcrops of the Devonian carbonates in the Świętokrzyskie Mts. According to results of the recent investigations (Urban 1999, 2000) majority of them represent Cenozoic forms or older forms that underwent modification during the Cenozoic. However recognition of their age – affiliation to the pre-Cenozoic or Cenozoic periods – was a matter of discussion for many years because of:

– modification of the older forms during the Cenozoic period,
– filling of the Cenozoic karst forms with the sediments derived from slightly weathered (disintegrated and redeposited) Zechstein or Buntsandstein rocks.

Although the existence of the Permian-Triassic paleokarst was supposed by several authors (e.g. Gradziński & Wójcik 1966, Majchert 1966), it was not proved in most of sites. For example, the paleokarst forms in Kadzielnia (Kielce) considered by Czarnocki (1949) and Kotański (1959) as Permian or Lower Triassic in age were interpreted as Tertiary by Rubinowski (1967).

Rubinowski (1967) tried to determine criteria to distinguish the pre-Cenozoic and Cenozoic karst forms. According to his opinion the essential criterion is relation to "honey-coloured calcite" veins representing the Early Triassic or younger mineralization. Thus paleokarst forms crossing these veins or filled with sediments containing fragments of "honey-coloured calcite", barite or galena, had to develop during the Cenozoic karst period. The occurrence of kaolinite clays, aggregates of limonite, as well as fragments of the Buntsandstein sandstones with desert varnish represent other features suggesting the Cenozoic age of the karst fills (Rubinowski 1967, 1971). Later Nawrocki (1987) used paleomagnetic method in order to distinguish the Permian-Triassic karst fillings from the Cenozoic ones.

Paleokarst forms of the Permian-Triassic age were described in several places: in Jaworznia quarry (Głazek & Romanek 1978, Głazek 1989), at Zelejowa Hill (Kardaś & Romanek 1978), in Zgórsko quarry (Bełka & Skompski 1978 – this site is inaccessible now), in Trzuskawica quarry (Motyka *et al*. 1993), in Wietrznia quarry (Szulczewski 1995b) and in Rzepka quarry (Migaszewski *et al*. 1996, Wierzbowski 1997). In 1986 underground paleokarst, pre-Cenozoic forms were found and described at the walls of chambers and galleries of Chelosiowa Jama cave in Jaworznia (Urban & Złonkiewicz 1989, Kuleta & Urban 1996). This fact mobilised the author to realise the study described below (see chapter "Methods").

METHODS

The study of the paleokarst in the Paleozoic core of the Świętokrzyskie Mts was performed in 1998–2000 by author (Urban 2000). It included field investigations of the Permian-Triassic and Cenozoic karst forms in natural and artificial outcrops as well as preliminary petrographic analyses of their fills. Petrographic analyses of the fills attributed to the Permian-Triassic karst period comprised optical microscopy of thin sections (more than 100) and several polished specimens, in some cases also cathodoluminescence. Samples collected in Jaworznia during investigations done in 1992–1993 were also used to the petrographic study. In order to identify the Permian and Triassic rocks, paleomagnetic analyses were carried out: in 1992–1993 – 8 samples from Chelosiowa Jama cave, in 1998–2000 – 9 samples collected in other sites. The paleomagnetic analyses were made in the Polish Geological Institute by dr J. Nawrocki. Several analyses of ^{13}C and ^{18}O content in calcareous cement of fills of the Triassic paleokarst forms in Chelosiowa Jama cave were realised by dr M. Duliński in Faculty of Physics and Nuclear Techniques, AGH University of Science and Technology in Kraków.

CRITERIA FOR IDENTIFICATION OF THE PERMIAN-TRIASSIC KARST AND ITS GENERATIONS

The evident features and analytic methods indicating the Permian or Triassic age of paleokarst forms and distinguishing them from the Cenozoic ones are following:

- structural position of forms directly under the rocks of the Zechstein, Buntsandstein or Muschelkalk – it is observed in a few sites only;
- paleontological evidences – the Cenozoic fossils were found in a few sites, they document the non-Permian-Triassic age of the paleokarst forms;
- original deposition of calcite, barite or galena representing the Permian and Early Triassic phases of hydrothermal mineralization (phases C, D – Migaszewski *et al*. 1996) in paleokarst forms – that is modified criterion of Rubinowski (1967), possible for application in rare cases of mineralization coexistent with karst;
- paleomagnetic properties of paleokarst fills – it is the most efficient method of dating, however there are many factors, which restrict the possibility of utilisation and interpretation of the paleomagnetic analyses (alteration of the ferruginous minerals, indistinct bedding and tectonic modification, rock compaction etc. – Nawrocki 1987);
- paleokarst forms older than tectonic structures of a known age – the feature observed only in one site.

Lithology of the paleokarst fills is not the evident feature distinguishing the paleokarst forms of two main periods and observations of the main features of the fills even brought about some mistakes in the past. But despite similarity in red color, detailed study shows petrographic differences between the sediments filling the pre-Cenozoic and Cenozoic paleokarst forms. The Permian and Triassic paleokarst fills are usually well lithified with calcareous cement, whereas the Cenozoic ones represent mainly loose sands and soft loams or coarse crystalline calcite speleothems. Predomination of calcite clasts and fragments of the Devonian carbonates as well as chemically precipitated limestone is often observed in the Triassic and Permian paleokarst fills, whereas material originated from weathering of the Buntsandstein clastics (quartz sandy grains) prevails in the Cenozoic ones (Urban 1999).

Lack of paleontological evidences and low precision of paleomagnetic analyses (enabling only distinction the Permian and Triassic sediments from the Cenozoic ones – Nawrocki 1987) cause that only structural and lithological features can be used for classification of individual generations of pre-Cenozoic paleokarst. These features were conditioned by geological evolution of the region, which was dissimilar in different places, thus they are not evident in some cases.

The classification is based on the following guidelines:

– The main phases of the hydrothermal calcite formation ("różanka" – Rubinowski 1971, phases B and C – Migaszewski *et al*. 1996) are linked with the Carboniferous--Permian, therefore paleokarst forms with this calcite should represent rather the Permian, than Triassic karst generations.
– Permian was the period of local denudation and short transport (Kowalczewski & Rup 1989, Zbroja 1995), thus sediments accumulated in this time contain exclusively local detrital material derived from the Devonian and older Paleozoic rocks.
– The allogenic material (quartz pebbles) appeared at the beginning of the Buntsandstein sedimentation (Senkowiczowa 1970), consequently the occurrence of the quartz pebbles in paleokarst fills proves the Buntsandstein or younger age.

GROUPS OF THE PERMIAN-TRIASSIC PALEOKARST

The directly post-Variscan karst period began just after the first subaerial exposition of the Devonian carbonates due to the tectonic movements (Kutek & Głazek 1972), that presumably happened in the Late Carboniferous. The karst period was terminated with the burial of the last outcrops of the Devonian carbonates, i.e. not earlier than in the early Middle Triassic. Paleokarst forms outcropped in 15 sites represent this karst period, now (plus one site, Zachełmie, with only erosional features). Almost all of them are situated in the western part of the Kielce subregion (Fig. 1).

Small number of the sites presenting the paleokarst forms and sequences of karst generations makes impossible the comprehensive reconstruction of all karst phases (*sensu* Bosak *et al*. 1989), thus hereafter in the text the informal "groups" of forms are described. The main criterion of the groups discrimination has been similar age and/or genesis of the karst forms (thus the group represents the same phase and generation) and/or similar circumstances of development and evolution (reflected in the shape or lithology of fills).

Two general types of forms can be distinguished (Tab. 1):

1) the older type, developed before the Buntsandstein sedimentation;
2) the younger one, developed during the Buntsandstein sedimentation and later.

Paleokarsts older than the Buntsandstein

The older paleokarst types and denudational forms are represented by four groups, as follows.

Pre-Buntsandstein surface karstification, erosion and gravitational mass movements (group I)

Description: Form belonging to this type occur in the abandoned quarry in Wietrznia situated in the southern flank of the Kielce Syncline (Fig. 1). In the quarry the thick-bedded and massive Givetian-Frasnian limestones dipping to the north are overlain with the thin-bedded Fammenian limestones and marls (Szulczewski 1995b).

The first object representing this group is extensive (60 m long) brecciation zone (Fig. 2, part of object A) formed of irregular fragments of light grey limestone (identical with surrounding massive Devonian rocks) sized from several centimeters to a few meters. The occurrence of irregular bands of light pink to red "cement" separating the limestone fragments enables to distinguish the brecciation zone from original Devonian rocks. The "cement" is formed of sparry calcite crystals of different size, irregular shape and curvilinear margins. The boundaries of micritic limestone fragments are often indistinct, partly altered into microsparite indicating recrystallization of the Devonian limestone. The recrystallization is also documented by discontinuous character of the bands in southern part of the brecciation zone blindly ending in limestone, as well as by irregular contours of limestone fragments with concave elements (Fig. 3). In some places (e.g. Fig. 2, part of object A, object B) the rock displays more advanced brecciation and transport of the limestone clasts. According to Szulczewski (1995b) the matrix of this breccia is lime mudstone and crinoid wackestone.

The second large formation belonging to this group represents mega-breccia body *ca* 500 m long (elongated in E-W direction), 150 m wide and 50 m thick (Szulczewski 1995b), located in the northern face and central part of the quarry (Fig. 2, objects C, D, E). The mega-breccia is composed of unsorted angular fragments of both Famennian and Frasnian limestones and marls (Fig. 4) of size varying from centimeters to several meters. The breccia matrix is formed of the limestone debris with smashed marls without traces of weathering. Also the clasts are not weathered.

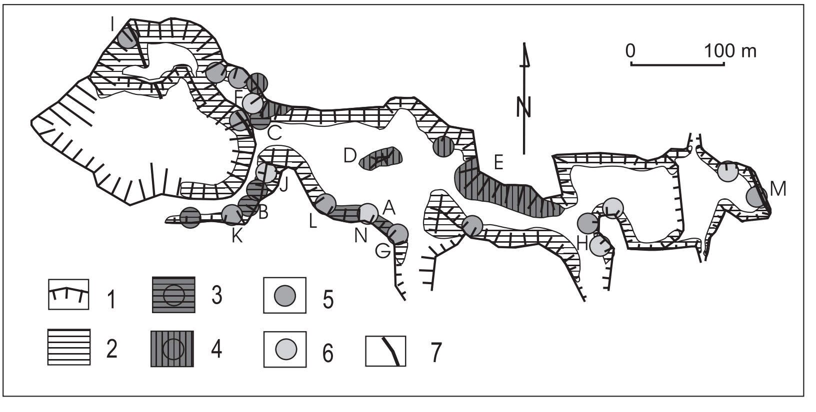


Fig. 2. Permian-Triassic paleokarst and other denudational forms in Wietrznia quarry. Explanations of symbols: 1 – quarry face, 2 – outcrops of the Devonian limestone, dolomite and marl, 3 – brecciation zone and similar breccias, conglomerates of the group I, 4 – colluvial mega-breccia (group I), 5 – limestone and marl filling the Permian-Triassic paleokarst forms (group IV), 6 – claystone and sandstone filling the Permian-Triassic paleokarst forms (group VIII), 7 – main fault. Explanation of letters in the text

Fig. 2. Permsko-triasowy kras kopalny oraz inne formy denudacyjne w kamieniołomie na Wietrzni. Objaśnienia symboli: 1 – ściana kamieniołomu, 2 – odsłonięcie dewońskich wapieni, dolomitów i margli, 3 – strefa brekcjowania i podobne brekcje oraz zlepieńce należące do grupy I form, 4 – megabrekcja osuwiskowa (koluwialna) (grupa I), 5 – wapień i margiel wypełniające formy paleokrasowe (grupa IV), 6 – iłowiec i piaskowiec wypełniający permsko-triasowe formy paleokrasowe (grupa VIII), 7 – główny uskok. Objaśnienia oznaczeń literowych w tekście

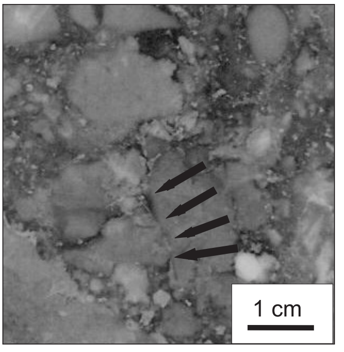


Fig. 3. Structure of the brecciation zone (group I) outcropped in the south face of the Wietrznia quarry (Fig. 2, object A). Grey fragments of the Devonian limestones are surrounded by brownish-red and orange "cement" (dark and light grey on the photo). The fragments do not resemble pebbles or debris – their margins are often indistinct and irregular, althought without sharp edges. The arrows indicate the discontinuous band of the initial alteration of limestone bringing about the disintegration of the limestone fragment and formation of two new "clasts"

Fig. 3. Tekstura strefy brekcjowania (grupa I) odsłoniętej w południowej ścianie kamieniołomu na Wietrzni (Fig. 2, obiekt A). Szare fragmenty wapieni dewońskich są otoczone przez brązowawo-czerwony i pomarańczowy „cement" (ciemno- i jasnoszary na zdjęciu). Fragmenty te nie przypominają otoczaków ani gruzu – ich granice są często niewyraźne i nieregularne, chociaż bez ostrych krawędzi. Strzałki wskazują nieciągłą strefę inicjalnej przemiany wapienia prowadzącej do dezintegracji fragmentu wapiennego i powstania dwu nowych „klastów"

Fig. 4. Mega-breccia – colluvium of landslide filling paleodoline (group I), well visible sliding surface of landslide. Wietrznia, northern face of the quarry (Fig. 2, object D)

Fig. 4. Megabrekcja – koluwium osuwiskowe wypełniające paleodepresję krasową (grupa I), dobrze widoczna powierzchnia poślizgu osuwiska. Wietrznia, północna ściana kamieniołomu (Fig. 2, obiekt D)

At the northern face of Wietrznia quarry (Fig. 2, object C) conglomerate composed of subrounded limestone fragments is exposed in the lower part of the mega-breccia formation (Figs 5, 6). In the same outcrop, matrix of the conglomerate and mega-breccia is partly replaced by calcite resembling hydrothermal calcite "różanka" (Fig. 6).

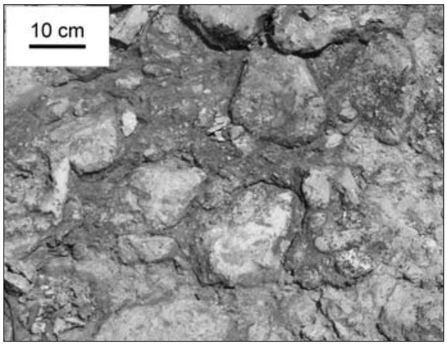


Fig. 5. Conglomerate overlain by the mega-breccia in the northern face of Wietrznia quarry (Fig. 2, object C)

Fig. 5. Zlepieniec przykryty przez megabrekcję w północnej ścianie kamieniołomu na Wietrzni (Fig. 2, obiekt C)

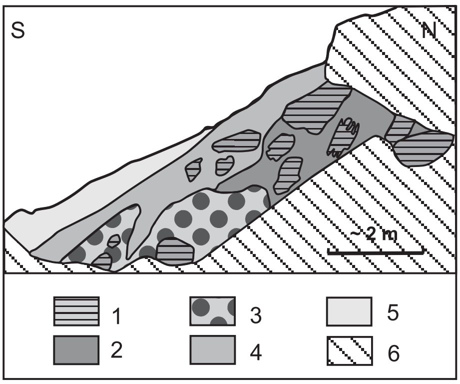


Fig 6. Succesion of the Permian-Triassic phases of denudation (karstification) outcropped in the northern face of Wietrznia quarry (Fig. 2, object C): older phases (group I) – conglomerate and mega-breccia, partly replaced by crystalline calcite; younger phase – karst form (chamber or pothole) filled with red claystone and siltstone with sandstone inserts (groups IV, VIII). Explanations of symbols: 1 – boulders of the Devonian limestone and marl, 2 – matrix of the mega-brecia, 3 – carbonate conglomerate (see Fig. 5), 4 – calcite resembling hydrothermal "różanka" calcite, 5 – claystone and siltstone with sandstone intercalations, 6 – current debris covering the quarry face

Fig. 6. Następstwo permsko-triasowych faz denudacji (krasowienia) odsłonięte w północnej ścianie kamieniołomu na Wietrzni (Fig. 2, obiekt C): starsze fazy (grupa I) – zlepieniec i megabrekcja, częściowo zastąpione przez kalcyt krystaliczny; młodsza faza – forma krasowa (komora jaskiniowa lub lej) wypełniona czerwonym iłowcem i mułowcem z wkładkami piaskowca (grupy IV, VIII). Objaśnienia symboli: 1 – bloki wapieni i margli dewońskich, 2 – matriks megabrekcji, 3 – zlepieniec węglanowy (patrz Fig. 5), 4 – kalcyt przypominający kalcyt hydrotermalny typu „różanki", 5 – iłowiec i mułowiec z wkładkami piaskowca, 6 – współczesny gruz przykrywający ścianę kamieniołomu

Interpretation: All above described breccias and conglomerate are older than Buntsandstein, because the karst sediments correlated with Buntsandstein discordantly overlay these lithified formations. Szulczewski (1995b) described the brecciation zone as "rock-matrix breccia" – the Permian sediment similar to "Zygmuntówka" conglomerate (deposit of alluvial fans – Zbroja *et al*. 1998), but it rather resembles the residual breccia described by Bełka & Skompski (1978) in Zgórsko quarry (in clasts' character and composition).

Following features:
– uniform lithology and large differences of size of limestone fragments,
– lack of clasts' abrasion (occurrence of only angular fragments),
– lack of quartz grains,

differ the breccia in Wietrznia from "Zygmuntówka" conglomerate.

The shape of some clasts and microscopic character of "cement" and clasts' margins suggest that at a least part of the brecciation zone was formed due to the alteration of the original Devonian limestones by recrystallization and disintegration connected with partial corrosion (see Dżułyński & Rudnicki 1986) developed along microfissures. This process could have taken place deep underground, but it also could have developed near surface, for example in the intermediate zone between rock basement and caliche cover (see Esteban & Klappa 1983). Short transport of clasts in a part of the brecciation zone suggests this second, near-surface environment (although no other remnants of caliche has been found, so far). Subsequently the rock was lithified again. If formation of this partly residual breccia had been related to near-surface alteration of rocks, the process could have started in the Late Carboniferous or Permian time, when denudation reached this zone.

The mega-breccia was described by Szulczewski (1995b) as "fitted megabreccia (...) abruptly created by a tectonic displacement of intensely karstified Devonian carbonates along the fault system". Developing this interpretation it can be stated that it is simply colluvium of a landslide formed (presumably during earthquake) in slopes of deep paleokarst depression – blind valley or doline. It is evidenced by:
– downward movement of blocks and debris (documented by lithological composition);
– considerable width of the mega-breccia body, which is not continued downward;
– character of its northern marginal surface (Fig. 4), with indistinct, weathered signs (slickensides) of downward, i.e. probably gravitational transport of the material.

Occurrence of the older conglomerate in the lower part of the mega-breccia (Fig. 6) confirms existence of the paleodepression before its formation. Identifying this conglomerate with the partly residual breccia outcropped at the south face ("rock-matrix megabreccia") Szulczewski (1995b) stated that the "fitted megabreccia" is younger than the "rock-matrix megabreccia".

Hydrothermal calcite "różanka" replacing the matrix of both conglomerate and mega-breccia (Fig. 6) suggests not later than the Permian age of the mega-breccia formation. The described above forms and sediments could have represented one or more than one karst phases.

Karstified tectonic fissures filled with hydrothermal calcite and clastic carbonates – Kowala-Nowiny type fissures (group II)

Description: The tectonic fissures filled with younger (but not the youngest) generations of hydrothermal calcite (phase C, Migaszewski *et al.* 1996) were locally modified by dissolution, as it is proved by karst runnels or wavy concave irregularities occurring on the walls of these fissures (widened even to 2–3 m). The veins with karstified boundaries have been found in (Fig. 1): Trzuskawica-Kowala quarry (Fig. 7), Kowala-Nowiny quarry (Fig. 8) and Łabędziów quarry.

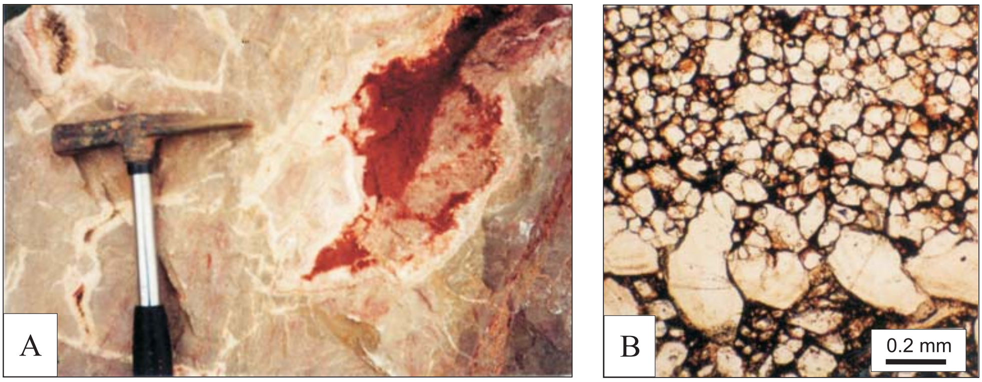


Fig. 7. Permian hydrothermal karst (group II): A) irregular, karst caverns developed along original tectonic crevices or joints, subsequently lined with drusy calcite "różanka" and filled with red clastic sediment; B) carbonate clastic sediment (sandstone) filling the cavern in microscale (concave-convex contacts of grains are visible); transmitted, plane polarized light. Trzuskawica-Kowala quarry

Fig. 7. Permski kras hydrotermalny (grupa II): A) nieregularne, krasowe kawerny rozwinięte wzdłuż pierwotnie tektonicznych szczelin i spękań, pokryte następnie szczotką kalcytową „różanki" i wypełnione czerwonym klastycznym osadem; B) węglanowy osad klastyczny (piaskowiec) wypełniający kawernę – obraz w mikroskali (widoczne są kontakty wklęsło-wypukłe ziarn); światło przechodzące, spolaryzowane, nikole równoległe. Kamieniołom Trzuskawica-Kowala

Fig. 8. Wide tectonic crevice with uneven walls due to the karstification (group II). The walls are covered with drusy calcite and the crevice is filled with sandy-carbonate rocks (marls grading to sandstones with conglomerate lenses). Large lenticular and nodular fragments revealed on weathered rock surface of the fill suggest slight redeposition of sediment. Kowala-Nowiny quarry

Fig. 8. Szeroka szczelina tektoniczna o nierównych, skrasowiałych ścianach (grupa II). Ściany pokryte są szczotką kalcytową, zaś szczelina wypełniona jest skałami piaszczysto-węglanowymi (marglami przechodzącymi w piaskowce z soczewkami zlepieńców). Duże soczewkowate i owalne fragmenty ujawniające się na zwietrzałych powierzchniach skalnych wypełnienia sugerują niewielką redepozycję osadu. Kamieniołom Kowala-Nowiny

The fissures are lined by 1–3 generations of white and pinkish-white coarse-crystalline calcite, whereas their central parts are filled with red-reddish brown marls and/or carbonate clastics (Figs 7, 8). Clastics are composed of silty and sandy grains of usually recrystallized sparry limestone and "różanka" calcite with admixture of fine quartz grains (Fig. 7B). The detrital grains are usually cemented with sparry calcite passing to micritic marl enriched in iron oxides. Irregular lenses of fine-grained conglomerate have been occasionally observed. The conglomerates are composed of the Devonian carbonates and well-rounded Cambrian or Lower Devonian quartzite pebbles as well as nodular fragments of sandy-calcareous rocks with blurred margins.

In some places the rocks filling the crevices reveal nodular or lenticular structure on the weathered surfaces (Fig. 8) related rather to different hardness than changes of the lithology. The nodular fragments reaching several to several tens centimeters are usually elongated parallel to the dykes' extension. This structure most probably reflects the tectonically or gravitationally triggered disturbances (and slight redeposition) of the fresh, weakly lit**hified sediment.**

Interpretation: Hydrothermal calcite and lithology of the detrital material (of local origin) indicate the Permian (Late Carboniferous) age of the karst dissolution. The process was connected with the thermal waters of deep circulation, from which the calcite precipitated (Rubinowski 1971). Occurrence of rounded pebbles of the local rocks suggests that some fissures were opened at the ground surface. It enabled inflows of the meteoric waters to the system and mixing with the thermal waters, as confirmed by isotopic composition of the calcite documenting variable temperature of its formation (25 to 122°C – Migaszewski *et al*. 1996). Influxes of the meteoric waters to some fissures could have been responsible for the karst corrosion of walls due to cooling and mixing of solutions of different compositions (see Ford & Williams 1989). Therefore dissolution is observed in restricted number of originally tectonic fissures only. The observed succesion of forms and sediments in the fissures (karstified walls, calcite linning and clastics filling) indicates that corrosion developed in the early stage of fissures evolution and – after the change of solutions' composition – precipitation of hydrothermal calcite started. Subsequent tectonic events opened fissures again and meteoric water carried silt, sand and pebbles downward from the surface. The slightly lithified sediments could have been redeposited during the next tectonic movements.

The exact number of karst phases characterised by the features described above is conditioned by the number of the tectonic activity stages, but till now it has been no reason to distinguish more than one phase.

Subsurface paleokarst forms and potholes filled with clastic carbonates (group III)

Description: Several subsurface forms with ovate and lenticular cross-sections (several decimeters to 2 m in diameter) as well as two forms, which might be interpreted as sinkholes represent this group. They were observed in Chelosiowa Jama cave, Jaworznia (Fig. 9, object B), Trzuskawica Nowa quarry, Rzepka-Korzecko quarry (Fig. 10), and Rzepka--Chęciny (probably sinkhole at least 3 m wide and 2 m deep – Fig. 11). The fills are bedded, usually red, brownish-red, beige and macroscopically resemble the Buntsandstein sandstones, but they differ from them in the composition of detrital material.

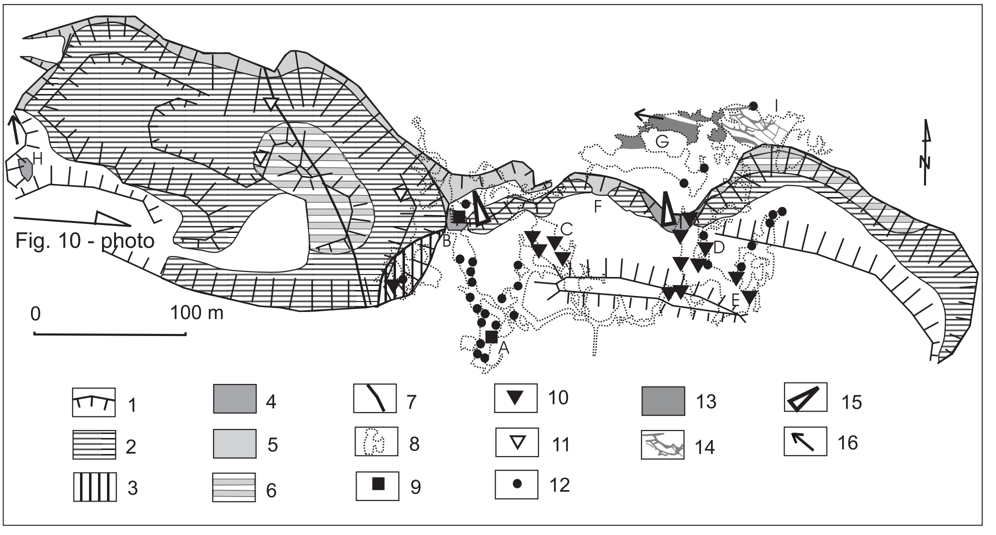


Fig. 9. Permian-Triassic paleokarst forms outcropped in Jaworznia quarries and Chelosiowa Jama--Jaskinia Jaworznicka cave system. Explanations of symbols: 1 – quarry face and other scarp, 2 – surface outcrop of the Devonian limestone, 3 – surface outcrop of the tectonic mega-breccia (limestone blocks in hydrothermal calcite), 4 – surface outcrop of the Buntsandstein mega-conglomerate (group VII), 5 – surface outcrop of the Buntsandstein sediments of Szczukowice Fm and Zagnańsk Fm (siltstone, sandstone and conglomerate), 6 – surface outcrop of the Devonian limestone strongly karstified or eroded (group VII), 7 – fault, 8 – contour of Chelosiowa Jama-Jaskinia Jaworznicka cave system, 9 – paleokarst form filled partly with hydrothermal calcite (groups III and IV), outcropped in the cave, 10 – paleokarst horizontal conduit – "large lense" (group VI), outcropped in the cave, 11 – "large lense" (group VI), outcropped at the surface, 12 – Permian-Triassic paleokarst form filled with sandy limestone (group V), outcropped in the cave, 13 – Buntsandstein mega-conglomerate (group VII), outcropped in the cave, 14 – "clastic veins" (group VIII) outcropped in the NPWZ Chamber of Jaskinia Jaworznicka cave, 15 – inclination of the paleoslope, 16 – direction of paleovalley. Explanation of letters and interpretation of the figure in the text

Fig. 9. Permsko-triasowy kras kopalny odsłonięty w kamieniołomach w Jaworzni oraz w systemie jaskiniowym Chelosiowej Jamy-Jaskini Jaworznickiej. Objaśnienia symboli: 1 – ściana kamieniołomu lub inna skarpa, 2 – odsłonięcie powierzchniowe wapieni dewońskich, 3 – odsłonięcie powierzchniowe megabrekcji tektonicznej (bloki wapienne spojone hydrotermalnym kalcytem), 4 – powierzchniowe odsłonięcie megazlepieńca związanego z sedymentacją osadów pstrego piaskowca, 5 – powierzchniowe odsłonięcie osadów formacji ze Szczukowic i formacji z Zagnańska (mułowce, piaskowce i zlepieńce), 6 – powierzchniowe odsłonięcie wapieni dewońskich silnie skrasowiałych i zerodowanych (grupa VII), 7 – uskok, 8 – kontur systemu jaskiniowego Chelosiowej Jamy-Jaskini Jaworznickiej, 9 – kopalna forma krasowa wypełniona częściowo kalcytem hydrotermalnym (grupy III i IV) odsłonięta w jaskini, 10 – kopalny kanał krasowy typu „wielkiej soczewy" (grupa VI) odsłonięty w jaskini, 11 – „wielka soczewa" odsłonięta na powierzchni, 12 – permsko-triasowa forma krasowa wypełniona wapieniem piaszczystym (grupa V), odsłonięta w jaskini, 13 – megazlepieniec pstrego piaskowca (grupa VII) odsłonięty w jaskini, 14 – „żyły klastyczne" (grupa VIII) odsłonięte w Sali NPWZ Jaskini Jaworznickiej, 15 – nachylenie paleostoku, 16 – kierunek paleodoliny. Objaśnienia oznaczeń literowych oraz interpretacja figury w tekście

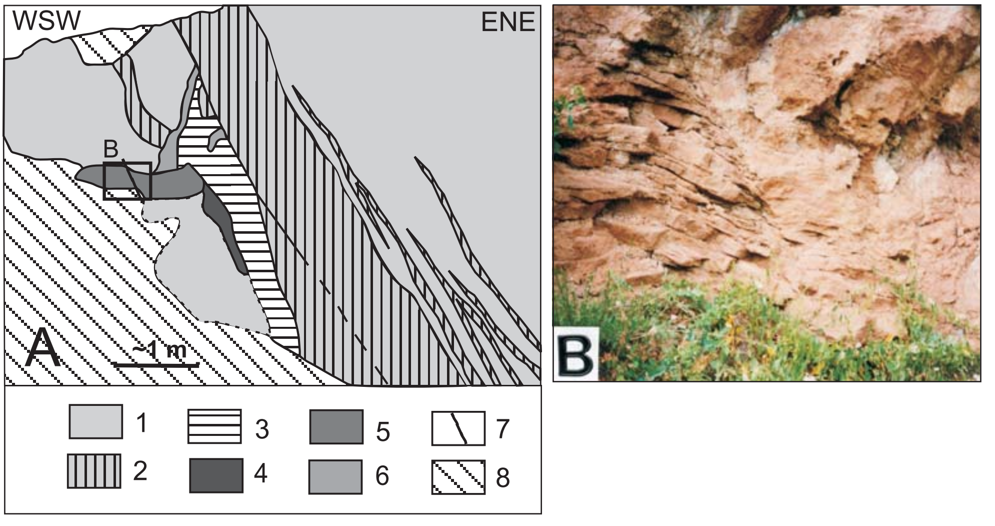


Fig. 10. Permian paleokarst form filled with carbonate clastic sediments (group III): A) relation of the form to vein of the hydrothermal calcite; B) lithology of the sediment filling the karst form. Rzepka-Korzecko quarry, locality commented by Migaszewski *et al*. (1996) and Wierzbowski (1997). Explanations of symbols: 1 – Devonian dolomite, 2 – coarse-crystalline hydrothermal calcite, 3 – calcite tectonic breccia, 4 – dark violet marl (fill of karst crevice?), 5 – red, carbonate sandstone in the karst form, 6 – loam – fill of the Cenozoic karst form, 7 – crack or small-scale fault, 8 – debris and grass covering the quarry face

Fig. 10. Permska forma krasowa wypełniona klastycznym osadem węglanowym (grupa III): A) stosunek formy do żyły kalcytu hydrotermalnego; B) litologia osadu wypełniającego formę. Kamieniołom Rzepka-Korzecko, stanowisko komentowane przez Migaszewskiego *et al*. (1996) oraz Wierzbowskiego (1997). Objaśnienia symboli: 1 – dolomity dewońskie, 2 – grubokrystaliczny kalcyt hydrotermalny, 3 – tektoniczna brekcja kalcytowa, 4 – ciemnofioletowy margiel (wypełnienie szczeliny krasowej?), 5 – czerwony węglanowy piaskowiec wypełniający formę krasową, 6 – glina – wypełnienie kenozoicznej formy krasowej, 7 – pęknięcie lub drobny uskok, 8 – gruz i trawa przysłaniające ścianę kamieniołomu

Sandy, locally silty, usually angular grains of hydrothermal calcite and limestone (or dolomitic limestone), often recrystallized prevail in the rocks. The carbonate detrital material is of local origin, delivered from eroded Devonian rocks (it is proved by clasts of flints, which occur in the Devonian limestones close to the site). So the rocks might be named calclithites (according to Folk 1959). Apart from the carbonate clasts, quartz grains (mainly fine-grained, silty) and fragments of siliceous-argillaceous rocks (up to 6% of the detrital material) as well as flakes of mica occur in the rock, too (Wierzbowski 1997). Detrital fragments are cemented by: sparry calcite (pseudosparite), calcareous-argillaceous-ferruginous material or argillaceous matrix with kaolinite aggregates. Locally carbonate clastics are accompanied with marls. Originally detrital grains of calcite and recrystallized limestone cemented by sparry calcite can be identified by cathodoluminescence (Fig. 11B, C).

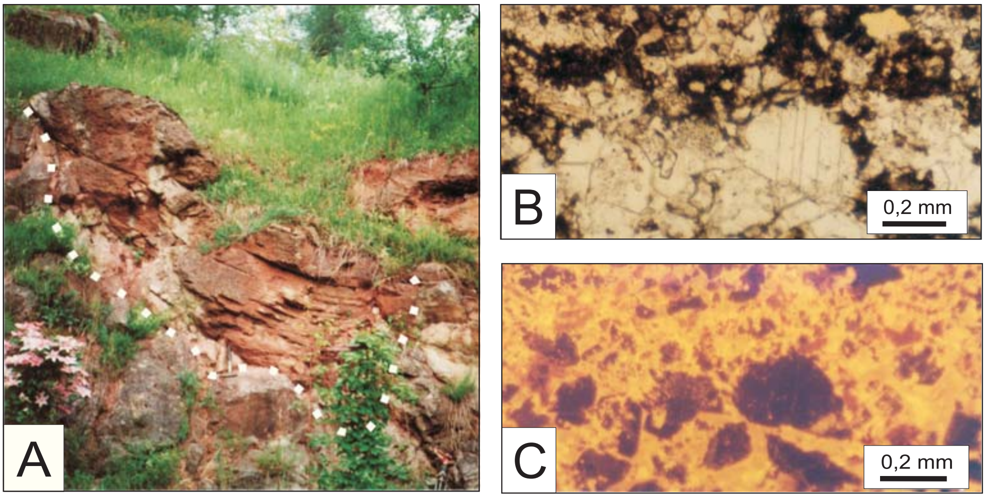


Fig. 11. Permian paleokarst form filled with bedded carbonate sandstones (group III): A) form in macroscale (margins of the form are signed by white dots); B) the fill in microscale; transmitted, plane polarized light; C) the same specimen in cathodoluminescence shows original detrital structure of the sediment. Rzepka-Chęciny

Fig. 11. Permska forma krasowa wypełniona uławiconym piaskowcem węglanowym (grupa III): A) forma w makroskali (granice formy podkreślone białymi kropkami); B) osad wypełniający w mikroskali, światło przechodzące, spolaryzowane, nikole równoległe; C) ten sam obraz mikroskopowy w katodoluminescencji ujawnia pierwotną, detrytyczną strukturę i teksturę osadu. Rzepka-Chęciny

Interpretation: Typical karst shape of forms indicates that dissolution was the predominant factor in their development. Lack of allogenic material and prevailing of carbonates suggest their affiliation to the Permian (Late Carboniferous?). In several cases the hydrothermal calcite linning the walls suggests the Permian age and connection with deep water circulation (Chelosiowa Jama cave, Jaworznia – Fig. 9, object B). The Permian-Triassic age is also documented by paleomagnetic analyses (Trzuskawica Nowa). The predominance of the local detrital material in the paleokarst fills indicates that the forms developed during intensive erosion of rough surface. There has been no cause to define more than one karst phase represented by the form belonging to the group III, so far.

Subsurface paleokarst forms and potholes filled with chemical carbonate deposits (group IV)

Description: This group is represented by several subsurface forms (possibly also sinkholes) similar to described above but filled with carbonates, marls and claystones without noticeable detrital component. They occur in the following sites: Wietrznia – large paleokarst form (cave chamber or sinkhole) filled with red and grey limestone, marl and claystone (Fig. 2, object F, Fig. 12) as well as several pipes and small subsurface conduits filled with red or beige marls and claystones (Fig. 2, objects G, I, K, L, M); Szczukowskie Górki quarry – two tubular forms (1–2 m in diameter) filled with grey, thin-bedded limestone (Fig. 13); Józefka quarry – lenticular (in cross-section) conduit filled with brownish-red limestone and marl; Komora Kryształowa (Crystal Chamber) in Chelosiowa Jama cave, Jaworznia (Fig. 9, object A) – 4 m long and 1.5 m wide chamber, which walls are lined with ca 0.5 m thick radial aggregates of large columnar crystals of hydrothermal ("różanka") calcite and central part is filled with grey, pink or red, thin-bedded limestone.

Fig. 12. Lower part of the large karst form (margins signed with white dots) filled with limestone and marl beds (group IV) which are tectonically broken (break signed with black line); the thickest limestone layer of the form fill (just under mudstone) pointed with arrow. The limestone-marl section is overlain by clay-siltstone section with sandstone inserts (group VIII not visible on this figure but marked on the figure 6). Wietrznia, north face of the west quarry (Fig. 2, object F)

Fig. 12. Dolna część dużej formy krasowej (granice podkreślone białymi kropkami) wypełnionej warstwami wapienia, margla (grupa IV) tektonicznie zdeformowanymi (miejsce przełamania zaznaczone czarną linią); najgrubsza ławica wapienia wskazana strzałką. Sekwencja wapienno-marglista przykryta jest osadami ilasto-mułowcowymi z wkładkami piaskowców (grupa VIII niewidoczna na tej figurze, ale zaznaczona na figurze 6). Wietrznia, północna ściana zachodniego kamieniołomu (Fig. 2, obiekt F)

Limestone in described forms displays sparite and microsparite fabric, locally with zones of micrite. Sparry crystals are anhedral, very irregular but generally equal. Alternation of fine crystalline (microsparite) laminae with irregular concentrations of argillaceous-ferruginous admixture and laminae formed of coarser crystals of pure calcite is frequently observed (Fig. 13). Recrystallization of the sparry fabric is evidenced by differentiation of crystal size (presumably stimulated by argillaceous admixture), irregular shape of crystals and their curvilinear contours. These features and lack of traces of carbonate detrital grains suggest direct precipitation of original sediment as "carbonate mud". Limestone bedding discordant to bedding of surrounding rocks excludes their formation due to direct recrystallization of the Devonian carbonates.

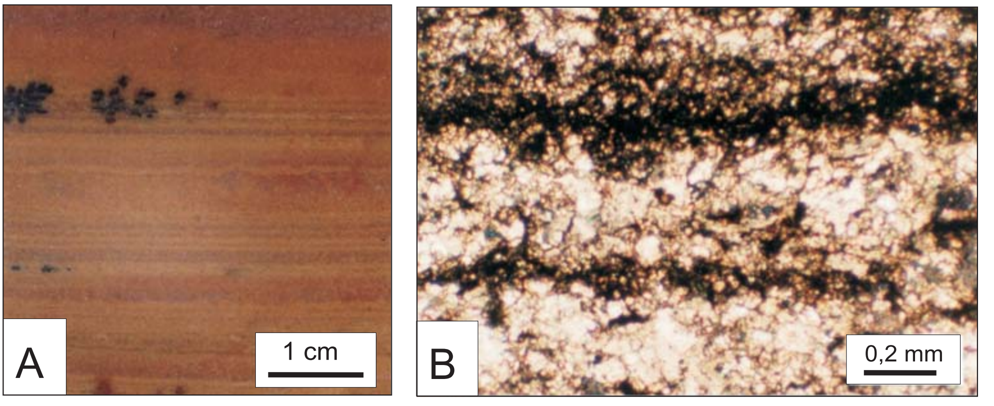


Fig. 13. Chemical limestone filling the Permian paleokarst forms (group IV): A) laminated limestone in macroscale, polished surface; B) the limestone in microscale; transmitted, plane polarized light. Szczukowskie Górki quarry

Fig. 13. Chemiczne wapienie wypełniające permskie formy krasu kopalnego (grupa IV): A) wapień laminowany w makroskali, powierzchnia wypolerowana; B) ten sam wapień w mikroskali; światło przechodzące, spolaryzowane, nikole równoległe. Kamieniołom w Szczukowskich Górkach

Very interesting sequence of the karst fills is observed in the several forms of the Wietrznia site, where gradual transition from the chemical carbonate rocks located in the lowermost parts of the profile to argillaceous (claystones) and even clastics – in the upper section is observed. For example in the large chamber open on the northern quarry face (Fig. 2, object F) the sequence of fill starts from the thin-bedded limestones and marls (Fig. 12) and grades upward to mudstones interbedded with siltstones and sandstones (of group VIII – see below).

Interpretation: Typical karst shape of forms indicates that dissolution predominated in their development. Lack of allogenic material and predomination of carbonates suggest their affiliation to the Permian, what is confirmed by other features observed in the sites as hydrothermal calcite linning (Chelosiowa Jama cave, Jaworznia – Fig. 9, objects A) and paleomagnetic analyses (Józefka, Wietrznia – Fig. 2, object G). Also the tectonic deformations of these forms (strata dip in Józefka, fault in Wietrznia – Fig. 2, object F, Fig. 12) are related probably to the Alpine movements, but their earlier generation is not excluded.

The forms presumably represent more than one phase of the paleokarst. The karst generations developed during the Permian time, most probably in the Late Permian (simultaneously to the deposition of PZ2-PZt sections of the Zechstein on the distal parts of the region), when morphology did not favour mechanic denudation: just before the deposition of the upper Zechstein (PZt), or on the area situated out of the deposition of the Zechstein, in the central part of the Paleozoic core, or after the denudation of the upper Zechstein. Probably the forms in Wietrznia, in which chemical limestones grade upward to marls, shales and clastic rocks are the youngest ones in this group, because the sandstones inserting the upper part of the sequence are very similar to ones of the Lower Buntsandstein. It suggests that these karst forms developed and were filled just before the deposition of the Buntsandstein on this area. They could have been contemporaneous with the development of the Early Triassic karst generation (phase) observed in Jaworznia site (and described below).

Early Triassic and younger paleokarst

Jaworznia site is the most interesting locality of the Early Triassic paleokarst, so should be more precisely characterised. It is situated in the marginal part of the tectonic block uplifted (in relation to the NW peripherial part of the region) at the beginning of the Buntsandstein sedimentation. Paleokarst formations and other denudational phenomena crop out in the abandoned quarries as well as in the passages and chambers of Chelosiowa Jama-Jaskinia Jaworznicka cave system situated within this area. The quarries and the cave are located in the Devonian limestones of the southern flank of the Kielce Syncline, dipping 20–30° to the north (Figs 1, 9, 14) and locally in the limestone-hydrothermal calcite tectonic mega-breccia. Uneven denudation surface of the Devonian rocks at the face of the Jaworznia quarry is covered by clayey-clastic lacustrine sediments of the Szczukowice Fm and fluvial sandstones of the upper Zagnańsk Fm of the Lower Buntsandstein (Głazek & Romanek 1978, Kuleta 1999, Kuleta & Zbroja 2006). The sediments of the Szczukowice Fm are much thicker behind the fault and paleoslope situated close to the north.

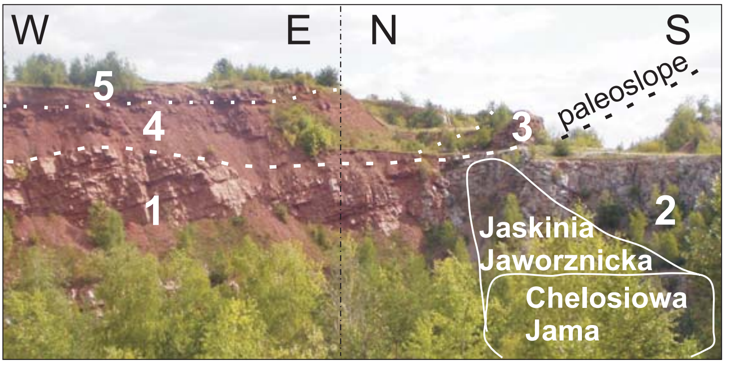


Fig. 14. North (W-E) and east (N-S) faces of the western quarry in Jaworznia with margins of the lithostratigraphic formations (dotted lines), the Devonian-Buntsandstein discordance (dashed line) and general location of the cave system Chelosiowa Jama-Jaskinia Jaworznicka (normal lines). Compare this photo with the map – Fig. 9. Explanations of symbols: 1 – Devonian limestones, 2 – limestone-calcite tectonic breccia, 3 – Buntsandstein mega-conglomerate, 4 – Szczukowice Fm, 5 – Zagnańsk Fm

Fig. 14. Północna (W-E) i wschodnia (N-S) ściana zachodniego kamieniołomu w Jaworzni z granicami jednostek litostratygraficznych (linie kropkowane), niezgodnością dewońsko-triasową (linia przerywana) i ogólnym położeniem systemu jaskiniowego Chelosiowej Jamy-Jaskini Jaworznickiej (linie ciągłe). Porównaj tę fotografię z mapką – Fig. 9. Objaśnienia symboli: 1 – wapienie dewońskie, 2 – wapienno-kalcytowa brekcja tektoniczna, 3 – megazlepieniec pstrego piaskowca, 4 – formacja ze Szczukowic, 5 – formacja z Zagnańska

Mostly horizontal Chelosiowa Jama-Jaskinia Jaworznicka cave is a maze system of passages and chambers 3.670 m long (western part of the system is called Chelosiowa Jama, whereas eastern fragment is called Jaskinia Jaworznicka). The system developed mainly during the Neogene (Urban 1996, 2002), but its elements often follow the pre-Cenozoic karst and erosional forms filled with lithified sediments (Fig. 9).

Subsurface paleokarst forms mainly filled with sandy limestones (group V)

Description: Most of the forms representing this group are karst conduits circular or lenticular in cross-section and horizontal or slightly inclined, but a few steeply dipping forms have been observed, too. They mainly crop out in the Korytarz Naciekowy gallery of Chelosiowa Jama cave (Fig. 9). The largest form (in Sala Deszczów chamber, next to Komora Kryształowa, Fig. 9, object A) is more irregular, at least 2.5 m wide and 1.3 m high (Fig. 15). The paleokarst forms are mainly filled with red or brownish-red, sandy (silty) limestone, occasionally shaly or thin-bedded, locally passing to almost pure limestone or calcareous sandstone (Fig. 16). The limestone is accurately lithified, occasionally porous or cavernous and composed of low-magnesium calcite coloured with iron oxides (Kuleta & Migaszewski 1994).

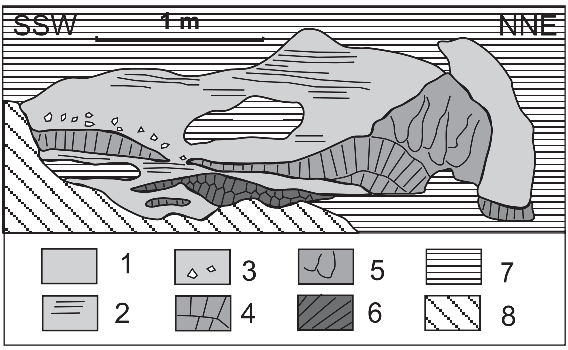


Fig. 15. The largest paleokarst conduit filled with red sandy limestone and calcite flowstone (group V). Chelosiowa Jama cave, Sala Deszczów chamber (next to Komora Kryształowa – Fig. 8, object A). Explanations of symbols: 1 – massive red sandy limestone, 2 – thin-bedded or shaly sandy limestone, 3 – sandy limestone with calcite aggregates, 4 – coarse-crystalline columnar calcite, cross-section of a flowstone, 5 – coarse-crystalline calcite, surface of a flowstone, 6 – coarse crystalline hydrothermal "różanka" calcite, 7 – Devonian limestone, 8 – current rock debris covering the form

Fig. 15. Największy kopalny kanał krasowy wypełniony czerwonym piaszczystym wapieniem i naciekami kalcytowymi (grupa V). Chelosiowa Jama, Sala Deszczów (obok Komory Kryształowej – Fig. 8, obiekt A). Objaśnienia symboli: 1 – nieuławicony czerwony piaszczysty wapień, 2 – cienkoławicowy lub łupkowy wapień piaszczysty, 3 – wapień piaszczysty z agregatami kalcytowymi, 4 – grubokrystaliczny kalcyt palisadowy, przekrój boczny nacieku, 5 – grubokrystaliczny kalcyt, powierzchnia nacieku, 6 – grubokrystaliczny kalcyt hydrotermalny typu „różanki", 7 – wapień dewoński, 8 – gruz skalny współcześnie przykrywający formę krasową

In microscopic scale two main structural types are distinguished:

1) Structure consisting of irregular but elongated forms up to 1 mm long, representing single crystals or – rarely – fan- or feather-shaped intergrowths of fiber crystals usually 0.03–0.5 mm long (Fig. 17B). Typical acicular-optic aggregates (see Kendall & Broughton 1978) with fascicular-optic features (Kendall 1985) have remained only on margins of caverns. In the larger crystals – representing recrystallized elements – original fibrous pattern are more or less apparently revealed as needles differing in yellow-brown tint. Consequently the whole rock reveals characteristic fibrous structure in not polarized light (Fig. 17A).

2) Structure consisting of crystals (usually up to 0.1 mm) of isometric shape but rough, sutured margins. More brown (ferruginous) patches are concentrated in marginal parts of the crystals forming arch- or cauliflower-shaped zones (Fig. 18). Occasionally transitional structure between this pattern and fibrous structure is observed.

Fig. 16. Fragment of paleokarst conduit (group V) outcropped in the Ser passage (close to Komora Kryształowa – Fig. 8, object A), filled with brownish-red, "shaly" limestone

Fig. 16. Fragment kopalnego kanału krasowego (grupa V) odsłoniętego w korytarzu Ser (w pobliżu Komory Kryształowej – Fig. 8, obiekt A), wypełnionego brązowawo-czerwonym, „łupkowym" wapieniem

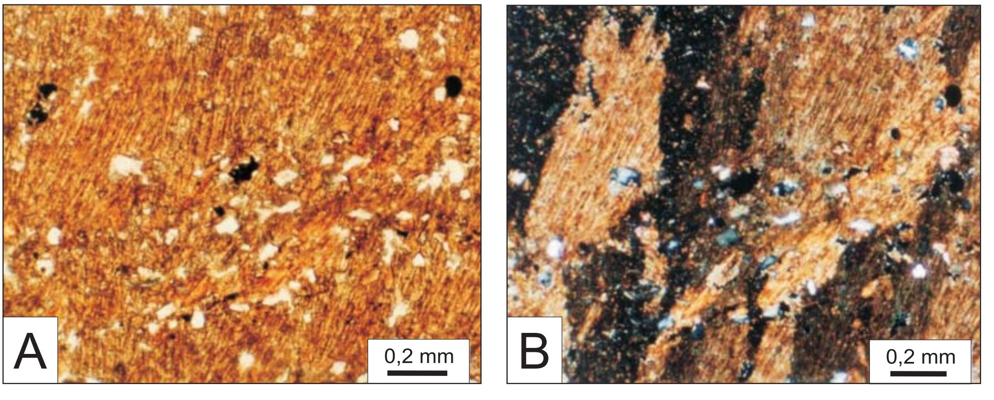
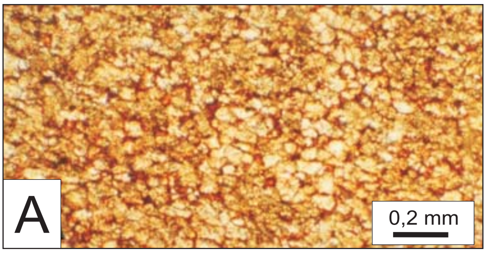


Fig. 17. The sandy limestone (group V) in microscale: A) transmitted, plane polarized light; B) transmitted, cross-polarized light. Remnants of fibrous fabric is well discernable in plane light due to ferruginization; quartz grains (white in the plane polarized light) do not influence the calcite structure suggesting its original, sedimentary character. Chelosiowa Jama cave, Korytarz Naciekowy gallery (Fig. 8, conduit connecting objects A and B)

Fig. 17. Wapień piaszczysty (grupa V) w mikroskali: A) światło przechodzące, spolaryzowane, nikole równoległe; B) światło przechodzące, spolaryzowane, nikole skrzyżowane. Pozostałości struktury włóknistej są dobrze widoczne w świetle przechodzącym przy nikolach równoległych dzięki obecności tlenków żelaza; obecność ziarn kwarcu (białych w świetle spolaryzowanym przy nikolach równoległych) nie wpływa na teksturę kalcytu, co sugeruje jej pierwotny, sedymentacyjny charakter. Chelosiowa Jama, Korytarz Naciekowy (łączący obiekty A i B na figurze 8)



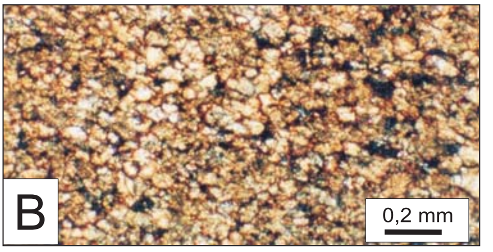


Fig 18. The sandy limestone (group V) in microscale: A) transmitted, plane polarized light; B) transmitted, cross-polarized light. Crystals are almost isometric and their fabric is discernable in plane polarized light due to occurrence of iron oxides. Chelosiowa Jama cave, Korytarz Naciekowy gallery (Fig. 8, conduit connecting objects A and B)

Fig. 18. Wapienie piaszczyste (grupa V) w mikroskali: A) światło przechodzące, spolaryzowane, nikole równoległe; B) światło przechodzące, spolaryzowane, nikole skrzyżowane. Kryształy są prawie izometryczne, zaś ich struktura widoczna jest w świetle przechodzącym, przy nikolach równoległych dzięki zażelazieniu. Chelosiowa Jama, Korytarz Naciekowy (łączący obiekty A i B na figurze 8)

Irregular, "cloudy" accumulations of silty or fine sandy grains of quartz occur in the both types of calcite fabric (Fig. 17), although horizontal laminae rich in clastic grains are observed, too. The quartz grains are poorly sorted and usually angular, with rare traces of regeneration and more frequent evidences of corrosion and replacement with calcite. Detrital grains form up to 20–30%, sporadically more than 50% of the rock composition (calcareous sandstones).

Irregular or lenticular bodies of white, yellowish-white or pink, coarse crystalline calcite, reaching lenght more than 1 m (Sala Deszczów chamber, Fig. 15) represent the second type of sediment filling paleokarst forms. Calcite bodies are usually nearly horizontal but some steeply inclined ones covering the walls of the paleoconduits are also observed. They consist of palisade columnar crystals revealing competitive growth.

Interpretation: Structures of yellowish-brown calcite reveal recrystallization of the majority of original, fan- or feather-shaped aggregates of fiber crystals and probably oxidation connected with separation of iron previously entrapped within the structure of crystals. Fiber (elongated) or irregular isometric calcite crystals most likely precipitated directly from solution forming rigid fabric having generally horizontal but uneven surface during deposition. Study of Gonzalez *et al*. (1992) indicating control of calcite crystals growth by an energy and direction of water flow, allows to interpret our structures as formed by calcite crystallization from water of different energy. Fiber crystals formed in flowing waters and direction of this growth depended on stream course, whereas isometric structures developed in stagnant water. Also Gradziński *et al*. (1997) linked development of acicular calcite crystals to high-energetic waters. Therefore it can be concluded, that limestone fills of paleokarst forms developed at the bottom of streams and pools. Sandy and silty-sized quartz grains were carried by streams and randomly accumulated on uneven ground.

Lack of structural traces of crystal phase transformation (see Folk & Assereto 1976, Assereto & Folk 1980) suggests that the original crystals were composed of calcite.

The second type of sediment filling paleokarst conduits – irregular or lenticular bodies of columnar calcite crystals – were formed due to the calcite precipitation in subaerial environment from thin films of solutions covering their surfaces and syntaxial crystal overgrowth (see Kendall & Broughton 1978). According to the classification proposed by Dziadzio *et al*. (1993) and Gradziński *et al*. (1997) they represent columnar microfacies of speleothems, which commonly develop in caves in subaerial but humid settings. It is suggested by shape of the calcite bodies, structure and smooth surfaces of the palisade layers as well as inner growth laminae (zones of aligned inclusions).

Structure of the fills evidences water table oscillations during the calcite precipitation. Most of the sediments were formed in subaqueous environment, but speleothems developed in subaerial conditions during lowering of the water table. Paleomagnetic analyses confirm the Permian-Triassic age of the forms. The forms cut veins of the hydrothermal calcite of "różanka" type and spatially occur next (to the south) and below the Lower Buntsandstein Szczukowice Fm, what suggest their Early Triassic age and development simultaneous to the deposition of this formation in the tectonically depressed area situated north of the Jaworznia horst. The system of paleoconduits of the group V represents no more than one karst phase (generation) and can be even presumed as an earliest part (event?) of the karst phase developed after morphological rejuvenation (see below).

"Large lenses" – horizontally expanded subsurface paleokarst forms (group VI)

Description: "Large lenses" represent large, horizontally extended forms, which crop out in the walls of Chelosiowa Jama cave and in the western quarry of Jaworznia (Fig. 9) as well as in active quarry in Szczukowskie Górki (Fig. 1). Shape of the "large lenses" cannot be recognized well within the cave as their horizontal size is often larger than present-day cave voids. Their observed height does not exceed *ca* 2 m, whereas lenght (width) reaches more than 20 m. The ceillings (most frequently observed) and floors (outcropped only in Sala z Kominem and Herbaciarnia chambers, Fig. 9, objects D, E, and in the quarry) are almost horizontal, flat and obliquely cross inclined beds of the Devonian limestones. Rare and thin karst fissures penetrate the Devonian up or down of the "lenses". The side walls are irregular or lenticular (Figs 19, 20), what motivates the name "large lenses".

The "large lenses" of Jaworznia are situated practically on the same level (250 m a.s.l.) in Chelosiowa Jama and several meters upper (253 m and 256 m a.s.l.) in three sites on the northern face of the quarry. Sites in the quarry are separated from Chelosiowa Jama cave with faults (Fig. 9).

The sequence of sediments filling these forms in Jaworznia is similar in every outcrop. The most characteristic is 0.5–1 m thick layer of conglomerate (conglomeratic sandstone) in the middle part of the fill (Figs 19, 20, 21).

The pebbles of this conglomerate, usually 0.3–0.8 cm in size, represent (Kuleta & Migaszewski 1994, Kuleta & Urban 1996):

– siliceous-argillaceous sandstones resembling the Cambrian, Ordovician and Lower Devonian rocks of the Dyminy Anticline (located south of the Kielce Syncline – Fig. 1) – subrounded to rounded pebbles constituting usually more than 40% of all fragments coarser than sands;

– calcareous-argillaceous, redish-brown sandstones having indistinct, blurred margins, what suggests their origin from weakly lithified sediments – more than 40%;
– quartz – small, well-rounded particles – *ca* 10% of pebbles.

The pebbles of shale, chalcedonite and carbonates occur occasionally.

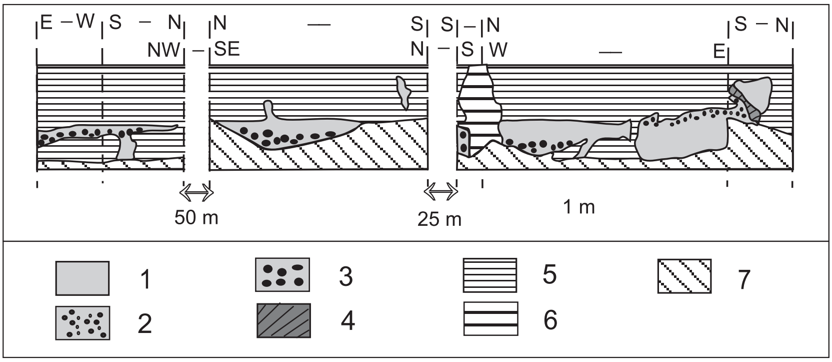


Fig. 19. The large paleokarst forms – "large lenses" (group VI): three outcrops in Chelosiowa Jama--Jaskinia Jaworznicka cave near Herbaciarnia chamber (Fig. 8, objects D and E). Explanations of symbols: 1 – sandy limestone or sandstone with calcareous cement, 2 – very fine grained conglomerate, 3 – conglomerate and conglomeratic sandstone, 4 – coarse crystalline hydrothermal "różanka" calcite, 5 – Devonian limestone, 6 – cave conduit (cavity), 7 – current rock debris covering the form

Fig. 19. Duże formy krasu kopalnego – „wielkie soczewy" (grupa VI): trzy odsłonięcia w systemie jaskiniowym Chelosiowej Jamy-Jaskini Jaworznickiej w okolicach sali Herbaciarnia (Fig. 8, obiekty D i E). Objaśnienia symboli: 1 – piaszczysty wapień lub piaskowiec o spoiwie węglanowym, 2 – bardzo drobnoziarnisty zlepieniec, 3 – zlepieniec lub piaskowiec zlepieńcowaty, 4 – grubokrystaliczny kalcyt hydrotermalny typu „różanki", 5 – wapień dewoński, 6 – korytarz jaskiniowy (pustka krasowa), 7 – gruz skalny współcześnie przykrywający formę krasową

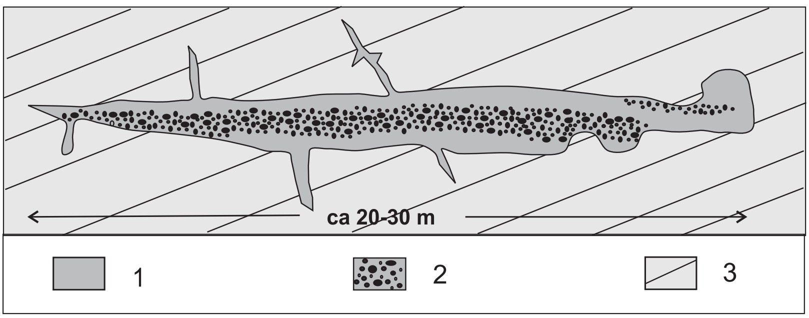


Fig. 20. Conceptual model (cross-section) of the "large lense" (group VI). Explanations of symbols: 1 – sandy limestone or sandstone with calcareous cement, 2 – conglomerate and conglomeratic sandstone, 3 – Devonian limestone (with bedding)

Fig. 20. Hipotetyczny przekrój „wielkiej soczewy" (grupa VI). Objaśnienia symboli: 1 – piaszczysty wapień lub piaskowiec o spoiwie węglanowym, 2 – zlepieniec lub piaskowiec zlepieńcowaty, 3 – wapień dewoński (z zaznaczonym uławiceniem)

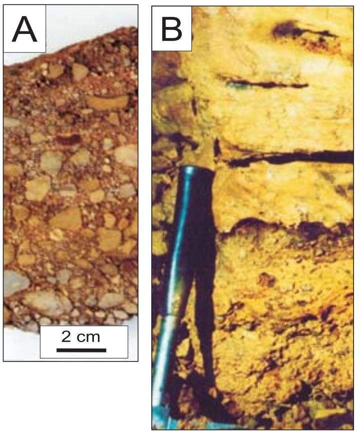


Fig. 21. The fills of the “large lenses” (group VI) in Chelosiowa Jama cave: A) conglomerate in Sala z Kominem chamber (Fig. 8, object C); polished surface; B) middle, conglomerate and upper, sandy-calcerous horizons in Herbaciarnia chamber (object D)

Fig. 21. Wypełnienia „wielkich soczew” (grupa VI): A) zlepieniec w Sali z Kominem (Fig. 8, obiekt C); powierzchnia wypolerowana; B) środkowy, zlepieńcowy i górny, piaskowcowo-wapienny poziom w sali Herbaciarnia (obiekt D)

Matrix of the conglomerate is composed of sandy and silty, poorly sorted subangular (when fine) to well-rounded (when coarse) detrital, mainly quartz grains (Kuleta & Migaszewski 1994, Kuleta & Urban 1996). The grains are cemented by recrystallized crystals of calcite reaching even a few milimeters. The calcite is partially basal but in places grain supported fabric occurs. Lenses with minor content of the detrital grains are composed of brown calcite with relics of fibrous structure resembling sandy limestone filling the small paleokarst forms (group V). Thin lenses of columnar calcite (similar to described in sandy limestones) occur in the upper part of the conglomerate layer.

Discontinuous blankets of sandy limestone grading to calcareous sandstone form lower and upper sections of the sequence of the “large lenses” fill (under and above the conglomerate). The sandstone resembles the matrix of the conglomerate, whereas the limestone is similar to sandy limestone filling smaller paleokarst forms (group V). Calcite in these beds displays remnants of fibrous fabric.

Isotope values $\delta\ ^{18}O$ (–7.91‰ to –7.45‰) and $\delta\ ^{13}C$ (–10.82‰ to –9.99‰) of calcite are very stable in the entire sequence of the fill of the “large lenses”.

The upper part of similar large paleokarst form with horizontal ceiling 50 m long, outcropped in the Szczukowskie Górki quarry (Fig. 1), is filled with loam representing originally lithified rocks, weathered during the Cenozoic. The fill contains lenses of silty-sandy limestone similar (in the fibrous structure) to the rock of the lower and upper units of the “large lenses” sequence in Jaworznia.

Interpretation: The “large lenses” cut the hydrothermal calcite veins and they very likely are nearly contemporaneous with the paleokarst forms filled with sandy limestone (group V), what is suggested by similar structure of the calcite.

Their Early Triassic age and concurrence with early Buntsandstein sedimentation is documented by:

- paleomagnetic analyses (Urban 2000);
- presence of volcanic clasts and composition of heavy-mineral assemblage (similar to the lowermost Buntsandstein – Kuleta & Migaszewski 1994, Kuleta & Urban 1996);
- difference between the elevation of the "large lenses" (conglomerate horizon) in the cave and in the Jaworznia quarry, which are separated with two faults (Fig. 9), active before the end of sedimentation of the Szczukowice Fm;
- occurrence of the quartz pebbles.

The "large lenses" in Jaworznia constituted a system of almost horizontal paleokarst cavities lenticular in cross-section, wide and very low. Specific shapes, especially extensive flat roofs, seem to result from the dissolution along practically stable water table. Horizontal roofs might be interpreted as "solution ceilings" (Lange 1962) related to water table or "Laugdecken" (Kempe *et al*. 1975), but shape of the whole forms denies these suggestions. Origin of the "large lenses" can be linked with mixing of waters of a different compositions. Gradual mixing of freshwater and sea water (brine) causes increase of aggressiveness in relation to calcium carbonate even if both original solutions are saturated (Rudnicki 1977). In the case of laminar flow of freshwater above salt water the direction of the highest aggressiveness is horizontal, what stimulates horizontal propagation of the karst cavities. The shape of the "large lenses" is similar to "flank margin caves" on the Bahamas formed on the level of halocline (Palmer & Williams 1984, Smart *et al*. 1988, Mylroie *et al*. 1991, Mylroie & Carew 2000). In the carbonates of the Moravian platform, similar to the limestones of the Kowala Fm in the age and lithology, the Middle Devonian paleokarst resembling caves on Bahamas were described (Bosak *et al*. 2002). However state of the diagenesis and tectonic evolution differ Jaworznia site from the paleokarst in Moravia and especially on the Bahamas. On the Bahamas the host rocks are aeolianites and beach grainstones, whereas in Jaworznia the rocks were hard, well lithified and tectonically deformed in the time of karstification.

Lithological and hydrological conditions of development of the "large lenses" can be compared with caves' formation in the Devonian limestones of Berry Head, Devon, where karst levels are related to the marine abrasion terraces developed during the Pleistocene (Proctor 1988). Paleokarst example of the corrosion in fresh and seawater mixing zones is represented with ore-filled paleocaves of Pine Point, Canada (Rhodes *et al*. 1984) and one of the oldest phase of paleokarst in the Black Hills, South Dakota (Palmer & Palmer 1989). Corrosional agressiveness on the level of halocline was observed also in the conduits with underground streams (Back *et al*. 1984).

Structures of the rocks filling "large lenses" and values of $\delta\ ^{18}O$ and $\delta\ ^{13}C$ indicate their origin in the freshwater conditions. Conglomerate deposited in relatively high energetic water flow of underground stream loaded with detritic material and dissolved calcium carbonate. The lenses of columnar calcite suggest local and periodic subaerial conditions.

Despite the fact that fills of the "large lenses" are freshwater sediments, the hypothesis on origin of these forms in fresh and sea water mixing zone is the simplest interpretation of their genesis. It is consistent with the paleogeographic conditions during marine ingresion related to the Permian-Triassic boundary (Pieńkowski 1991, Kuleta & Zbroja 2006). There is no evidence suggesting tectonic or lithologic control of the “large lenses” origin. Their horizontal extend indicates low hydrostatic gradient and unconfined hydrological conditions. It means that limestone was densely fractured or/and karstified (conduits of the V group) before the formation of the “large lenses”. Sea level had to be stable at least for a few hundreds thousands years and also freshwater recharge should have been lasting continuously during the same time. In the climate of the Early Triassic it could be possible when fissured-karst aquifer of the Devonian limestones was fed through porous clastics of the overburden. Karst forms were rapidly widened in the fresh and salt water mixing zone, what caused concentration of water flows and formation of low and wide underground horizontal channels (or channel).

The detrital material of conglomerate (pebbles) originated from:

– the Lower Paleozoic rock of the Dyminy Anticline outcropped several kilometres south of Jaworznia,
– partly lithified Zechstein sediments deposited in the inner part of the Paleozoic core and eroded after the tectonic movements preceding Buntsandstein sedimentation,
– allogenic material transported from the area situated south of the region.

So the “large lenses” represent the later part of the karst phase (event?) simultaneous with the Buntsandstein deposition on the depressed foreland of the region.

Surface paleokarst and other denudational forms contemporaneous with the deposition of the Lower Buntsandstein (group VII)

Description: This group is represented by various erosional-karst forms of the Devonian carbonates’ surface filled and overlain with the Buntsandstein sediments. They have been described in Doły Opacie, Zachełmie and Jaworznia. In Doły Opacie small karst hollows, occurring on surface of the Devonian dolomite and covered by the Buntsandstein (Barczuk 1979) are inaccessible now. In Zachełmie quarry (Szulczewski 1995c) only erosional paleoforms occur – mechanically widened fissures and small V-shaped channels developed along bedding planes of dolomites and covered by the Buntsandstein. Such features indicate that dolomites underwent fluvial and gravitational processes. Lack of karst relief is caused by fast erosion and occurrence of marl inserts in the dolomites.

The paleosurface of the Devonian limestones is exposed in the northern face of Jaworznia quarries and in Jaskinia Jaworznicka cave (Fig. 9). The limestone surface is covered by mega-conglomerate formed of limestone blocks and outcropped in the central part of the quarries (Figs 14, 22). The mega-conglomerate passes to the north in the distance of a few dozen meters to interbedded mudstone and thin-bedded pebbly sandstone of the Szczukowice Fm (Głazek & Romanek 1978, Kuleta 1999). Głazek & Romanek (1978) described karst microforms (not exposed now) and larger depression interpreted as potholes and filled with red mudstone of the Jaworznia Fm (Fig. 9, object H).

Some chambers of Jaskinia Jaworznicka cave (Fig. 9, object G) are located within the mega-conglomerate resembling sediment outcropped in the quarry. It is composed of limestone blocks characterised by corrosional surfaces and brownish-red, clayey-detrital, fine-grained (sandy) matrix.

Fig. 22. The mega-conglomerate covering the paleoslope of the Devonian limestones; north face of the middle quarry in Jaworznia (east of object F on the figure 8)

Fig. 22. Megazlepieniec przykrywający kopalne zbocze zbudowane z z wapieni dewońskich; północna ściana środkowego wyrobiska w Jaworzni (na wschód od obiektu F na figurze 8)

Interpretation: The paleorelief and lithology of the Buntsandstein sediments suggest that during this time the Devonian limestones in Jaworznia formed slope gradually eroded and burried by debris and mud-debris flows, which swept down the slope and deposited in the lake at foothill during the sedimentation of the lower Buntsandstein. The gravitational sediments on the paleoslope and its foothills passed to the north to the lacustrine facies of the Szczukowice Fm (Kuleta 1999). In the less inclined paleosurface karst microrelief and larger forms – as pothole or gully – developed (Głazek & Romanek 1978, Głazek 1989). According to Nawrocki (1997) reversed paleomagnetic polarity of the pothole (gully) fills suggests their Permian age, but Fijałkowska and Kuleta (Fijałkowska 1994, Fijałkowska & Kuleta 1994, Kuleta 1999) basing on palynology, confirm the Early Triassic age.

Observations in Jaskinia Jaworznicka cave supplement the paleogeographic interpretation presented above. Mega-conglomerate is a slope sediment, formed of boulders with surfaces karstified before or after gravitational transport. The shape and spatial situation of the mega-conglomerate body indicate that it covers a paleo-slope cut with a paleo-valley (or two valleys), trending from ESE to WNW (Fig. 9).

Underground forms filled with the Buntsandstein sandstones – mainly "clastic dykes" (group VIII)

Description: Fissures cutting the Devonian carbonates and filled with sandstones of the Buntsandstein were observed in several sites of the south-western part of the Paleozoic core by Majchert (1966), Głazek & Roniewicz (1976) and – in Jaworznia – by Głazek & Romanek (1978). Detailed observations in several outcrops indicate that the fissures have usually straight, flat walls of tectonic origin, but corrosional relief of the walls is noted occasionally. In Wietrznia and Jaworznia sites the fissures are filled with very fine-grained sandstones (lithic arenites) composed of mainly subangular quartz grains (*ca* 60%), fragments of rocks and micas (often altered to kaolinite). The grains are cemented with calcareous, calcareous-ferrugineous or calcareous-argillaceous material (Fig. 23).

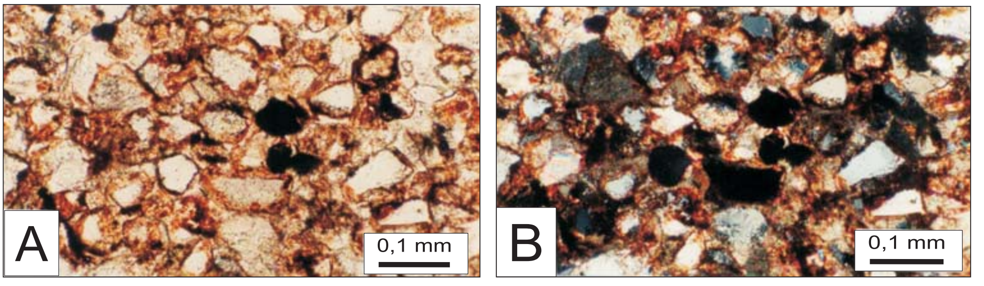


Fig. 23. Lithic arenite insert in the upper part of the sequence of sediments filling the large karst form (group VIII) in the north face of western part of Wietrznia quarry (Fig. 2, object E) in microscale: A) transmitted, plane polarized light; B) transmitted, cross-polarized light. Quartz angular and subangular grains predominate, but grains of iron oxides, altered carbonates and silico-argillacous rocks are visible, too

Fig. 23. Arenit lityczny tworzący wkładkę w górnej części sekwencji osadów wypełniających dużą formę krasową (grupa VIII) w północnej ścianie zachodniej części kamieniołomu na Wietrzni (Fig. 2, obiekt E) w mikroskali: A) światło przechodzące, spolaryzowane, nikole równoległe; B) światło przechodzące, spolaryzowane, nikole skrzyżowane. Przeważają ostrokrawędziste i słabo obtoczone ziarna kwarcu, liczne są jednak również ziarna tlenków żelaza, zwietrzałych skał węglanowych i krzemionkowo-ilastych

In Jaworznia the fissures (up to 3 m wide) developed in the limestone massif in head part of the paleovalley (gorge) described above. They are pretty exposed in Jaskinia Jaworznicka cave (Fig. 9, object I) forming network on roof of the NPWZ chamber. Among them straight tectonic joints of WNW-ESE (longitudinal) direction predominate, but several slightly bended fissures represent forms induced by the gravitational massif relaxation. Fissures do not display karst relief but in a few places their lowermost parts pass to paleokarst conduits filled with the same type of sediment.

The same type of lithic arenites form several inserts in the red-brown claystone--mudstone in the upper part of the sequence filling the large chamber in Wietrznia (described in group IV, Fig. 2 object F). According to Szulczewski (1995b) fine quartz pebbles occurred in the uppermost part of the sequence of similar sediments outcropped in the southern face of the quarry (Fig. 2, object G). Nearby fissure filled with the lithic arenite cut the older brecciation zone (Fig. 2, object N). Walls of this fissure show dissolutional relief, whereas the flute marks on the bedding plane of sandstones filling the fissure indicate deposition in water stream.

The karstification of the fissures found in the Kadzielnia site is not proved, whereas the "clastic dyke" found at the Zamkowa Góra hill, Chęciny represent purely tectonic form. Lithology of the fissure fills in Kadzielnia is more similar to the fluvial sandstones of the Zagnańsk Fm, Lower Buntsandstein. Its Triassic age is confirmed by the paleomagnetic analyses.

Interpretation: Majchert (1966) suggested karst origin of the fissures cutting the Devonian carbonates, whereas Głazek & Roniewicz (1976) interpreted them as "clastic dykes" opened due to the tectonic activity, what is documented by their straight extension, flat walls, slickensides and angular fragments of the Devonian carbonates within their fills. The slickensides in Jaworznia indicate the domination of horizontal tectonic displacement (Głazek & Romanek 1978). Shape and variable width of the dykes in this site indicate also significant role of the dilation and gravitational displacement of separated massifs close to the paleoslope in the widening of the cracks. In Wietrznia site the karst corrosion is proved by dissolutional runnels on the walls of the fissure filled with sandstone.

Close connection between the "clastic dykes" formation and the Buntsandstein sedimentation in Jaworznia is proved by their occurrence directly below the Szczukowice Fm and confirmed by paleomagnetic analyses. Lithology of fills in Jaworznia and Wietrznia are very like to each other and similar to the sandstones of the Szczukowice Fm (see Kuleta 1999), what suggests that the forms in Wietrznia were also filled during the sedimentation of the lowermost Buntsandstein. Different lithology of the "clastic dyke" in the Kadzielnia site may suggest later burrying of this element of the Paleozoic core by the Buntsandstein sediments.

The karst corrosion of the tectonic fissures developed directly before the Buntsandstein deposition represents the last episode (event?) of the Early Triassic karst phase.

Paleokarst forms filled with the carbonates of the Röt or Muschelkalk (group IX)

Description: Paleokarst forms filled with limestones of the Röt or Muschelkalk were identified in two sites. The first one is situated in uplifted tectonic element in Strawczyn (western margin of outcrop of the Paleozoic core – Fig. 1), where the Devonian carbonates are overlain directly with the Röt and Muschelkalk. The Devonian/Triassic boundary, partially representing structural discordance (now inaccessible), was exposed due to the barite exploitation in the first half of the 20. century (Czarnocki 1958, Rubinowski 1971). Although forms of relief were not topics of those study, figure published by Czarnocki (1958) shows paleocave developed in the Devonian limestones, filled with conglomerate and covered by the limestones of the Łukowa Beds.

Forms filled with light grey, thin-bedded limestone were found in Wymysłów quarry, eastern part of the Paleozoic core (Fig. 1) and they are represented with two shafts up to 1 m and 2 m in diameter and at least 2 m deep (Fig. 24A). The fill of shafts is formed of sparite and microsparite laminae differing in crystal size. Calcite crystals are anhedral and at least partly recrystallized, but relics of rare litho- or bioclasts are discernible. Rare light brown elongated clasts resemble fragments of algal mats with indistinctly preserved internal structure. Small rhombic and triangular most probably dolomite crystals (or their pseudomorphoses) coloured with iron oxides are dispersed in calcite matrix (Fig. 24B). Irregular ("cloudy") accumulations of often euhedral gypsum crystals up to 2 mm long occur in places. But white, discoidal gypsum or calcite-gypsum aggregates 2–5 mm in diameter apparently discriminated from the rock background at bedding planes (rarely found also inside the beds) are the most interesting features. According to A. Radwański (pers. commun., 2000) they are syneresional forms.

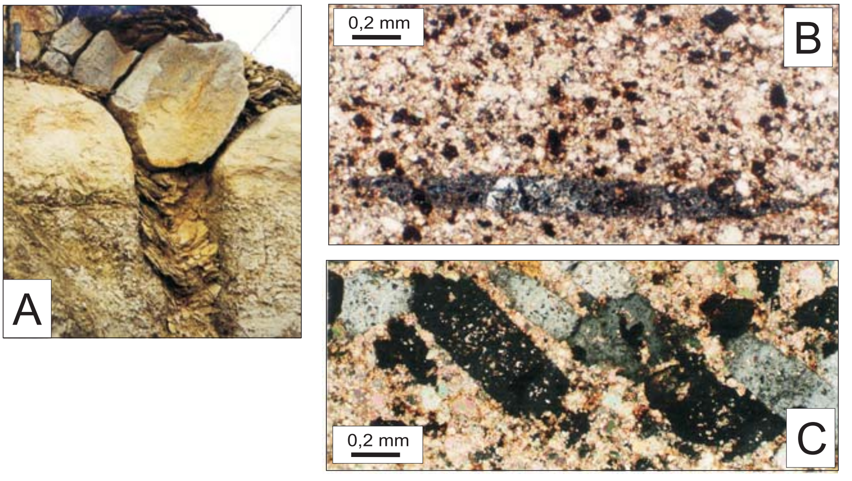


Fig. 24. The youngest Triassic paleokarst generation (group IX): A) karst shaft filled with the thin-bedded limestone of the Röt or Muschelkalk; B) limestone in microscale: gypsum-calcite lens in the neosparite, brown agregates of triangular and rhombic shape represent likely altered dolomite crystals or their pseudomorphoses; transmitted, cross polarized light; C) limestone in microsale: euhedral gypsum crystals in the neosparite; transmitted, cross polarized light. Wymysłów quarry

Fig. 24. Najmłodsza generacja krasu triasowego (grupa IX): A) studnia krasowa wypełniona cienkoławicowym wapieniem retu lub wapienia muszlowego; B) wapień w mikroskali: gipsowo-kalcytowa soczewka w kalcytowym neosparycie, brązowe agregaty o trójkątnym lub rombowym kształcie stanowią najprawdopodobniej zwietrzałe kryształy dolomitów lub ich pseudomorfozy; światło przechodzące spolaryzowane, nikole skrzyżowane; C) wapień w mikroskali: idiomorficzne kryształy gipsu w kalcytowym neosparycie; światło przechodzące spolaryzowane, nikole skrzyżowane. Kamieniołom Wymysłów

Interpretation: The both paleokarst sites should be referred to the Muschelkalk or Röt. The Early Anisian age of form in Strawczyn is proved by its position under the Łukowa Beds, Lower Muschelkalk. The limestone filling forms in Wymysłów resembles thin-bedded rocks described by Pawłowska (1979) in the Muschelkalk, rarely in the Röt sequence in southeastern part of the Permian-Mesozoic cover of the Świętokrzyskie Mts. Its Permian-Triassic age is confirmed by the paleomagnetic analysis.

Occurrence of the dolomite and gypsum crystals in the sediments in Wymysłów indicates high mineralization of water and evaporation as one of the main factors stimulating precipitation. Paleokarst forms were situated most probably in marginal zone of evaporation basin (marine or inland) providing mineralized water. Periodic separation of the forms from this basin is probably marked by formation of syneresional aggregates developed due to dessication or diffusional migration of solution from freshly deposited sediment to the higher mineralized (condensed due evaporation) solution above the sediment surface.

The both sites represent the youngest karst forms of the Permian-Triassic karst period in the region. The form in Strawczyn developed during probably short geological event of the tectonic block uplift, whereas the Wymysłów site could have represented the ultimate event of the long-lasting Early Triassic karst phase (generation) of the south-eastern segment of the Świętokrzyskie Mts region.

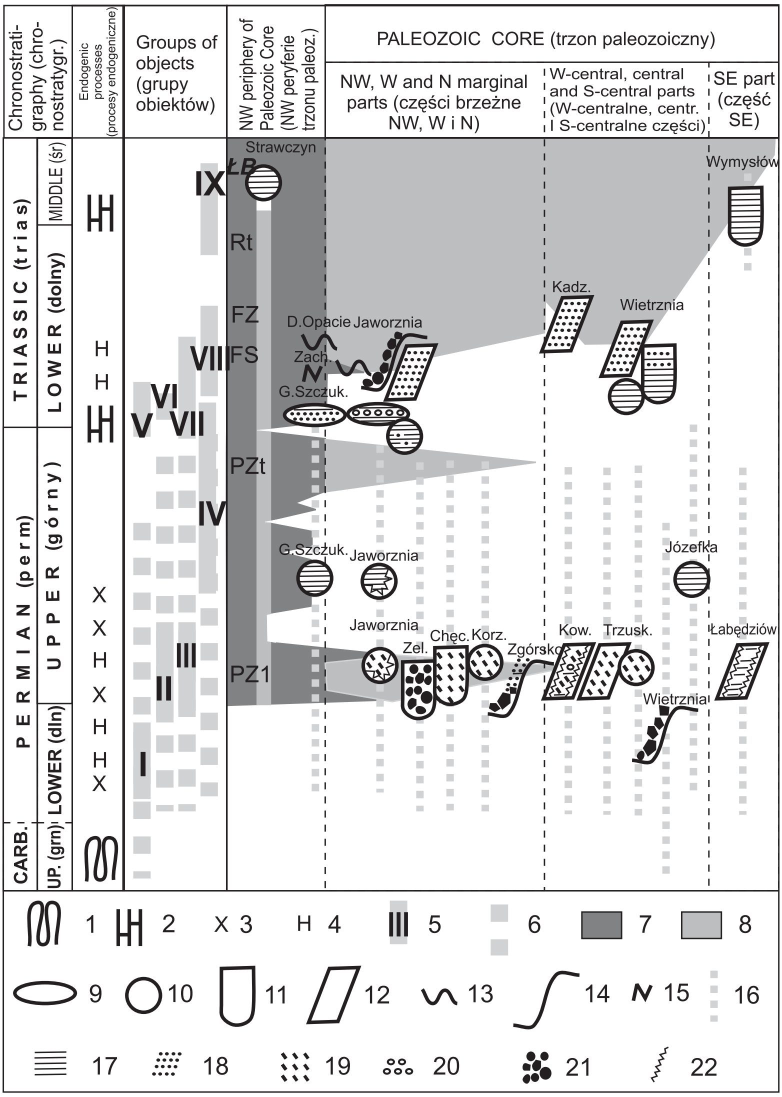
GEO(MORPHO)LOGICAL EVOLUTION OF THE ŚWIĘTOKRZYSKIE MTS RECORDED IN THE PALEOKARST

The Permian and Triassic karst in the Świętokrzyskie Mts developed during the last phases of the Variscan tectonic movements and initial stage of the Danish-Polish Trough formation. The Paleozoic core of the Świętokrzyskie Mts, uplifted in the Late Carboniferous, was gradually subsided and burried by sediments during the Permian and Triassic time (Kutek & Głazek 1972, Hakenberg & Świdrowska 1998). Denudational phenomena (karst forms) document evolution of the region during this terrestial period.

The oldest forms of karstification, i.e. mega-breccia in Wietrznia (group I), karstified calcite-detrital veins (group II) and karst cavities filled with the detrital sediments (group III), indicate rough morphology, intensive erosion of local rocks and significant role of tectonic movements (Tab. 1 on the interleaf, Fig. 25). The mega-breccia in Wietrznia (group I) formed due to the gravitational movements on the steep slope of the large karst depression, likely triggered by an earthquake. The calcite-detrital veins (group II) with corroded walls were tectonic fissures reaching the ground surface. Meteoric waters deeply penetrated the fissures and mixed with thermal waters generating karstification. The tectonic opening of the fissures at the surface indicates their origination due to the tensional strains predominating in the Zechstein basin (see Kutek & Głazek 1972, Znosko 1989). The destruction of the calcite incrustations and remobilization of freshly lithified detrital fills of the fissures were caused by frequent tectonic movements, probably earthquakes. Common occurrence of clasts of local carbonate rocks in fills of the paleokarst and tectonic forms (groups II, III) suggests conditions convenient for rather mechanical than chemical corrosion: hot and arid climate, rough (mountainous?) relief and probably frequent earthquakes.

The paleokarst forms preceeding the Buntsandstein deposition, characterised by the corrosional shape and chemically precipitated carbonate or argillaceous (marly) fills (group IV) likely developed when the climate was more humid (see Wagner 1994, Fijałkowska 1994) and represent presumably at least two phases (generations) of different age (Tab. 1, Fig. 25). The older ones could have developed between the deposition of carbonate-detrital sediments of the lower Zechstein PZ1 and formation of the clastics rocks of the upper Zechstein PZt, when conditions were not favorable for the mechanical erosion and relief was more or less flat (as suggested by lack of clastics in PZ2 and PZ3 – Kowalczewski & Rup 1989, Kuleta & Zbroja 2006), and the Devonian carbonates were not yet covered by the PZt sediments deposits or they were not covered by these deposits at all (in the inner part of the Paleozoic core).

The younger – and the youngest pre-Buntsandstein – karst generation formed during and after denudation of the Zechstein deposits caused by the late Permian/early Triassic tectonic movements and relative uplift of some massifs (Tab. 1, Fig. 25). These tectonic movements (suggested by Kowalczewski & Rup 1989) are proved by the occurrence of fragments of originally weakly lithified sandstone pebbles in the conglomerates of the "large lenses" in Jaworznia (group VI), delivered from the Zechstein rocks covering the western part of the Paleozoic core south of the Jaworznia site, which were denuded before and even contemporary with the Buntsandstein deposition on the relatively lowered area situated NW of the Paleozoic core (Fig. 25). The youngest pre-Buntsandstein karst phase is also represented by several objects in Wietrznia. Their formation and filling started before the deposition of the Buntsandstein in the surrounding area (what does not mean that it preceded this deposition in the whole region), but ultimate filling was corelated with the beginning of the Buntsandstein deposition there. It is recorded by lithology of fills, which grades from chemically precipitated carbonates (group IV representing the Zechstein) at the bottom of the sequence to sandstones of the Buntsandstein (group VIII) at its top (Fig. 25).



Although the Świętokrzyskie Mts area is considered to be peripherial to the Variscan Orogenic Belt (Pożaryski *et al*. 1992) the presented study proves that their geo(morpho)-logical evolution in the Permian time resembles in some aspects external regions of the Variscan Orogene, characterised by the extensional tectonics. Similar processes of the tectonic disintegration, formation of calcite veins related to hot water springs and karst corrosion occurred during the Permian time in the Kraków-Silesian region (Paszkowski & Wieczorek 1982, Szulc & Ćwiżewicz 1989, Felisiak *et al*. 2000). The Permian-Triassic paleokarst influenced by the thermal waters and connected with the opening of vertical cracks have been also observed in several regions of the south Britain, e.g. the Derbyshire, Mendip Hills and Devon (Ford 1989) as well as in the Sardinia, Italy (Boni & Argenio 1989).

Fig. 25. The development of the Permian and Triassic paleokarst and other denudational forms in the Świętokrzyskie Mts. Explanations of symbols: 1–4 – endogenic processes influencing karstification: 1 – main phase of the Variscan tectonic movements, 2 – faulting, relative uplift and depression of tectonic blocks, 3 – possible faulting, earthquake, 4 – thermal waters circulation in the near-surface zone; 5–6 – groups of karst (and denudational) forms: 5 – the most probable period of the development of the group signed by number, 6 – possible time of the development of the group; 7–8 – deposition of sediments: 7 – sediments existing now (FS – Szczukowice Fm, FZ – Zagnańsk Fm, Rt – Röth, ŁB – Łukowa Beds), 8 – sediments denuded in the Permian-Triassic and Cenozoic; 9–15 – types of karst and denudational forms and phenomena with names of the sites (abbreviated names: D.Opacie – Doły Opacie, G.Szczuk. – Górki Szczukowskie, Zach. – Zachełmie, Kadz. – Kadzielnia, Zel. – Zelejowa, Korz. – Rzepka-Korzecko, Chęc. – Rzepka-Chęciny, Kow. – Kowala-Nowiny, Trzusk. – Trzuskawica-Kowala and Trzuskawica Nowa): 9 – "large lense", 10 – subsurface conduit or chamber, 11– pothole or karst shaft, 12 – tectonic crevice with karstified walls, 13 – small surface karst forms on (sub) horizontal paleosurface, 14 – slope (slope processes and sediments), 15 – (sub)horizontal erosional paleosurface without traces of karstification, 16 – time span of possible development of form (if distinctly extends the size of the symbol); 17–22 – sediments filling the forms: 17 – chemical limestone, dolomite, marl or claystone, 18 – quartz or lithic sandstone (with non-calcareous grain predominance), 19 – carbonate sandstone (calclithite), 20 – fine-grained conglomerate or conglomeratic sandstone, 21 – coarse-grained conglomerate, mega-conglomerate, mega-breccia, brecciation zone (residual breccia), 22 – hydrothermal calcite

Fig. 25. Rozwój permskiego i triasowego krasu kopalnego oraz innych form denudacyjnych w Górach Świętokrzyskich. Objaśnienia oznaczeń: 1–4 – procesy endogeniczne wpływające na rozwój krasu: 1 – główna faza tektonicznych ruchów waryscyjskich, 2 – tworzenie się uskoków, względne wynoszenie i obniżanie bloków tektonicznych, 3 – możliwe ruchy blokowe, trzęsienia ziemi, 4 – krążenie wód termalnych w strefie przypowierzchniowej; 5–6 – rozwój grup obiektów krasowych (lub denudacyjnych): 5 – najbardziej prawdopodobny okres rozwoju grupy form krasowych oznaczonych numerem, 6 – możliwy okres rowoju grupy form krasowych; 7–8 – sedymentacja osadów: 7 – osady obecnie istniejące (Fs – formacja ze Szczukowic, FZ – formacja z Zagnańska, RT – osady retu, ŁB – warstwy łukowskie), 8 – osady zdenudowane w permie, triasie i kenozoiku; 9–15 – typy form krasowych oraz innych zjawisk denudacyjnych z nazwami stanowisk (objaśnienie skróconych nazw – patrz angielski opis figury): 9 – „wielka soczewa", 10 – podpowierzchniowy korytarz lub sala jaskiniowa, 11 – lej lub studnia jaskiniowa, 12 – szczelina tektoniczna ze skrasowiałymi ścianami, 13 – małe powierzchniowe formy krasowe na słabo nachylonych lub poziomych powierzchniach, 14 – zbocze (procesy i osady zboczowe), 15 – słabo nachylona (pozioma) paleopowierzchnia erozyjna bez śladów krasowienia, 16 – okres możliwego rozwoju formy (jeśli przekracza wyraźnie wielkość symbolu na figurze); 17–22 – osady wypełniające formy: 17 – wapień chemiczny, dolomit, margiel, skała ilasto-mułowcowa, 18 – piaskowiec kwarcowy lub lityczny z przewagą ziarn niewęglanowych, 19 – piaskowiec węglanowy, 20 – drobnoziarnisty zlepieniec lub piaskowiec zlepieńcowaty, 21 – grubodetrytyczny zlepieniec, megazlepieniec, megabrekcja, strefa brekcjowania (brekcja rezydualna), 22 – kalcyt hydrotermalny

It suggest that the Świętokrzyskie Mts were influenced by the Stephanian-Early Permian wrench tectonics and the Early Permian extensional strains (see Ziegler 1990).

The denudation of the Zechstein sediments on the Paleozoic core south of Jaworznia before and contemporary with the Buntsandstein deposition (see above) proves that Jaworznia and presumably other areas, in which the post-Variscan paleosurface is covered directly with the Buntsandstein (Szczukowskie Górki, Zachełmie, Doły Opacie) do not represent relics of mountainous relief of the Permian (as it was stated by ome authors, e.g. Skompski 1995), but were morphologically rejuvenated due to the late Permian/early Triassic tectonic movements, related to the initial stage of the Danish-Polish Trough formation (see Ziegler 1990, Hakenberg & Świdrowska 1998). These movements caused lowering of the vast tectonic blocks in the western and northern foreland of the region and relative elevation of the inner part of the Paleozoic core (Kowalczewski & Rup 1989). The marginal fragments of relatively uplifted blocks of proximal part of the Paleozoic core underwent fast denudation, whereas the north-western part of the region was being gradually and diachronically covered with the Buntsandstein. It is recorded by development of the surface and underground karst forms of the Early Triassic karst phase (groups V, VI, VII) in the marginal fragments of these blocks (Tab. 1, Fig. 25). Also the sediments formed in various – subaerial and subaquaeos – conditions, which fill the karst conduits suggest differences of morphological elevation. In the Jaworznia tectonic block (horst) even the scale of rejuvenation of paleorelief can be assessed. Assuming that the "large lenses" (group VI) represent "underground streams" having outlets situated at the level of the lowered foreland (what is proved by conglomerate fill), the tectonically generated elevation of the paleohill can be estimated at about 50 m or more.

The occurrence of the "large lenses" in two sites (Jaworznia, Szczukowskie Górki) suggests intensive subsurface water discharge in carbonate parts of uplifted blocks and existence of "subsurface streams" in cliffs facing lowlands of northwestern foreland. Their existence during the deposition of the Szczukowice Fm correlated with the marine ingression referred to the Zechstein/Buntsandstein and Permian/Triassic boundary (see Pieńkowski 1991) proves similar age of the strongest tectonic movements. But the tectonic movements – horizontal and vertical – were continuing at least to the end of the sedimentation of the Szczukowice Fm, as recorded by faults active in this time (crossing and shifting the "large lenses" and not rejuvenated later). In the Jaworznia site the karst phenomena developed in this time (firstly groups V and VI, subsequently VII and VIII) coexisted with mechanical erosion as well as tectonic and gravitational movements. The tectonic-gravitational fissures were opened and filled with detrital material of the Buntsandstein (Tab. 1). Formation of the "clastic dykes" in many sites (Głazek & Roniewicz 1976) suggests still tensional nature of the tectonics.

Western and partly central fragments of the Paleozoic core were burried by the sediments of the Lower Buntsandstein, what is documented by several outcrops of paleosurface and – where the original Triassic sediments are totally eroded – by remnants of the Buntsandstein clastics in the Cenozoic karst forms (Urban 2000). Pre-Cenozoic paleosurface is overlain by the sediments of the Szczukowice Fm in majority of outcrops (Jaworznia, Szczukowskie Górki, Zachełmie, Doły Opacie). Only in Kadzielnia site the lithology of the "clastic dyke" fills migh suggest direct burrying by other lithostratigraphic unit (Zagnańsk

Fm) (Fig. 25). Burrial of the Devonian carbonates by the Buntsandstein obviously halted karst process. Horst of Strawczyn (with the paleokarst site) seems to be exclusive morphological form in the western part of the region. It was tectonically uplifted and emerged in (or close before) the Middle Triassic (Anisian), despite rather strong subsidence of this part of the region in this time. So the formation of the paleocave in Strawczyn represents rather incidental event in the geological history of the region.

Lack of the Lower to Middle Buntsandstein cover and even remnants of redeposited rocks of this age in the Cenozoic paleokarst forms in the central and eastern parts of the region confirms suggestion of Senkowiczowa (1970) about nondeposition of these sediments there. It is proved in Wymysłów, where the pre-Cenozoic paleokarst forms are filled with the Röt or Muschelkalk. However the single site can not be representative for the whole eastern part of the region, especially if paleokarst form filled with the Muschelkalk in Strawczyn situated in the western part of the region is related to the small tectonic horst. The forms in Strawczyn and Wymysłów represent the youngest phase (phases) of the pre-Cenozoic karst in the region (Tab. 1, Fig. 25).

CONCLUSIONS

The Permian-Triassic karst period in the Świętokrzyskie Mts was connected with the Variscian tectonic movements and uplift as well as initial stage of formation of the Danish-Polish Trough. It lasted some 70 Ma and is represented with forms developed in the Devonian carbonates. The Permian-Triassic paleokarst and denudational forms have been identified and distinguished from the Cenozoic ones on the basis of paleomagnetic analyses as well as paleontology (Pleistocene fossils), relation of paleokarst forms to the Variscian calcite mineralization and structural position of these forms, where it was possible. But in many cases these methods could not be used, therefore the petrographical differences between the Permian-Triassic and Cenozoic paleokarst fills have been used for their discrimination. The most characteristic features differing these rocks are: composition and structure of rocks and state of their lithification.

Several groups of the denudational-karst forms have been classified. The older, Permian karst and denudational phases are represented by:

- subsurface and surface forms of karstification (conduits, chambers, dolines), which are filled with detrital sediments of local origin (calclithites);
- karstified tectonic fissures, developed probably in the zones of mixing of thermal waters (of deep circulation) and cold (meteoric) waters and filled with calcite incrustations and detrital sediments.

These tensional tectonic cracks were often opened to the surface. The shape of the karst forms and lithology of fills indicate climatic and morphological conditions favourable for mechanical erosion – arid climate and rough relief. Active tectonic movements, e.g. earthquakes, played significant role in the Permian evolution of the region.

The group of the subsurface karst forms developed also before the Buntsandstein deposition but filled with chemical limestones and marls are attributed to the karst phases (rather more than one phase) contemporaneous with the upper Zechstein (PZ2-PZt) sedimentation on the distal parts of the region.

Younger, Triassic phase of the karstification started after the period of the Late Permian sedimentation and was triggered by the tectonic reconstruction of the region, which consisted in disintegration and relative subsidence/elevation of the tectonic blocks. In morphologically elevated marginal parts of the blocks the denudation of the Zechstein and older rocks developed, whereas in the depressions (situated mainly in the north-western parts of the region karst the lowermost Buntsandstein sediments deposited. The network of the subsurface, conduits formed in the Devonian carbonates of the marginal parts of the uplifted blocks. Among them were horizontal, wide and low tunnels ("large lenses"), which were presumably formed in the mixing zone of salt and fresh waters during the marine ingression reaching the north-western periphery of the region at the Permian/Triassic boundary. The small conduits are filled with chemically precipitated limestones containing admixture of quartz sandy grains, whereas in the sequence of sediments filling large tunnels the characteristic unit of conglomerate occurs.

The next stage of the tectonic movements (still of the tensional character) directly preceded the deposition of the Buntsandstein (which burried the Devonian carbonates at least in the western part of the region) and resulted in the development of the tectonic fissures ("clastic dykes") with signs of karst corrosion. These fissures and some typical paleokarst forms were filled with sandstones very similar to rocks of the lowermost Buntsandstein.

The youngest paleokarst phase (phases?) is (are?) represent by two sites, in which forms are filled with carbonate sediments of the Muschelkalk (Anisian) or Röth. The paleocave located on the western part of the Paleozoic core developed due to the uplift and emergence of the tectonic block. The second object, located in the eastern part of the region suggests lack of Buntsandstein cover there, which is also confirmed by lack of the Buntsandstein rocks redeposited to the Cenozoic karst forms in this part of the region.

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Streszczenie

Na terenie Gór Świętokrzyskich znane są formy krasowe reprezentujące trzy okresy:

1) dewoński, związany z lokalnymi wynurzeniami podczas sedymentacji skał węglanowych;
2) karbońsko(?)-permsko-triasowy, spowodowany górnokarbońskimi oraz późniejszymi ruchami tektonicznymi;
3) kenozoiczny.

Celem artykułu jest opis typów form reprezentujących permsko-triasowy kras kopalny, ocena ich wieku i genezy oraz sformułowanie wniosków dotyczących ewolucji geologicznej i morfologicznej regionu.

Odróżnienie form krasu permsko-triasowego od kenozoicznych form krasowych jest trudne ze względu na policykliczność procesu krasowego oraz wypełnianie form kenozoicznych materiałem pochodzącym ze skał cechsztynu lub pstrego piaskowca. Metody analityczne i zjawiska pozwalające na stosunkowo pewne odróżnienie form należących do obu okresów krasowych to badania kierunków paleomagnetycznych oraz inne analizy wieku bezwzględnego i badania szczątków fauny, a także stosunek form krasowych do mineralizacji kalcytowej oraz zjawisk tektonicznych i skał o określonym wieku. Praktyczne możliwości wykorzystania tych wskaźników są zwykle niewielkie, dlatego też w ocenie przynależności poszczególnych form krasowych do danego okresu znaczenie zyskują petrograficzne różnice pomiędzy wypełnieniami form permsko-triasowych i kenozoicznych, wynikające z od-

miennych warunków sedymentacji oraz innych źródeł materiału. Do cech odróżniających wypełnienia form permsko-triasowych i kenozoicznych należą:

- odmienny skład petrograficzny i struktury,
- odmienny stopień lityfikacji i tekstury,
- różne formy występowania tlenków żelaza.

Formy krasowe i denudacyjne reprezentujące permsko-triasowy okres lądowy, który trwał około 70 mln lat, są obecnie odsłonięte w 15 stanowiskach zlokalizowanych głównie w południowo-zachodniej części trzonu paleozoicznego (Fig. 1). Do najciekawszych stanowisk, w których odsłania się sukcesja form, należą kamieniołomy w Jaworzni oraz na Wietrzni (Fig. 2, 9, 14).

Niewielka liczba stanowisk umożliwia jedynie ogólne wyróżnienie dwu typów form krasowych i denudacyjnych (Fig. 25, Tab. 1):

1) powstałych przed sedymentacją pstrego piaskowca,
2) powstałych i wypełnionych w trakcie sedymentacji pstrego piaskowca oraz później.

Typ starszy reprezentowany jest przez następujące grupy form:

- strefy dezintegracji skał węglanowych (zbrekcjowania wapieni) oraz obszary intensywnej erozji i korozji krasowej reprezentowane przez brekcję wapienną oraz zagłębienie wypełnione osuwiskową megabrekcją wapienno-marglistą (Fig. 2, 3, 4, 5, 6);
- szczeliny tektoniczne, zmodyfikowane krasowo w strefach mieszania się wód termalnych i meteorycznych; wypełnione kalcytem, piaskowcami wapiennymi i marglami (Fig. 7, 8);
- kanały krasowe i prawdopodobnie powierzchniowe zagłębienia krasowe wypełnione podobnymi, choć zwykle drobnoziarnistymi osadami detrytycznymi (np. piaskowcami wapiennymi (Fig. 9, 10, 11);
- kanały i komory krasowe wypełnione wapieniem chemicznego pochodzenia (Fig. 12, 13).

Młodszy etap denudacji oraz krasowienia nastąpił po okresie depozycji górnopermskiej i wywołany został przebudową tektoniczną regionu na początku sedymentacji utworów pstrego piaskowca. Przebudowa ta, związana z tworzeniem się bruzdy duńsko-polskiej, spowodowała rozpad regionu na bloki obniżające się w kierunku północno-zachodnim. W strefach brzeżnych zrębów, stanowiących jednocześnie morfologiczne wzniesienia skały trzonu paleozoicznego oraz ich permska pokrywa ulegały denudacji, podczas gdy w obniżeniach trwała już sedymentacja pstrego piaskowca.

Do najważniejszych przejawów ówczesnego krasu i innych procesów rzeźbotwórczych należą:

- sieć kanałów wypełnionych wytrąconymi chemicznie wapieniami piaszczystymi (Fig. 15, 16, 17, 18);
- kanały o rozmiarach poziomych znacznie przewyższających wysokość, tzw. „wielkie soczewy", które powstały prawdopodobnie w strefie mieszania się wód słodkich oraz słonych na brzegu ingresji morskiej przełomu permu i triasu; wypełnione zlepieńcami i piaskowcami wapnistymi (Fig. 19, 20, 21);
- doliny i blokowiska na zboczach zrębowych wzniesień morfologicznych (Fig. 22);
- szczeliny tektoniczne i grawitacyjno-odprężeniowe miejscami zmodyfikowane przez procesy krasowe i wypełnione piaskowcami (Fig. 23).

Najmłodsza faza (krasowa) udokumentowana jest przez dwie formy wypełnione osadami retu lub wapienia muszlowego (Fig. 24). Jedna z nich zlokalizowana jest w obrębie zrębu tektonicznego na zachodnich obrzeżach regionu, druga – we wschodniej części trzonu paleozoicznego. Położenie tej drugiej oraz litologia wypełnień krasu kenozoicznego we wschodniej części regionu (brak osadów redeponowanych z klastycznych skał pstrego piaskowca) sugeruje brak pokrywy pstrego piaskowca w tej części regionu.

Przeprowadzone studia form i wypełnień krasowych udowodniły zależność pomiędzy aktywną tektoniką uskokowo-blokową a rozwojem rzeźby regionu (Fig. 25, Tab. 1). Tektonika o charakterze tensyjnym, powiązana z krążeniem wód termalnych upodabnia region świętokrzyski do obszarów orogenu waryscyjskiego (południowo-zachodnia Polska, masyw czeski itp.) w późnej fazie tych ruchów górotwórczych.

Table (Tabela) 1

Development of karst forms at the background of geological evolution of the Paleozoic core of the Świętokrzyskie Mts (PcŚM). Numbers – sites according to figure 1, capital letters – objects on figures 2 and 8, Roman numbers in brackets – groups of the paleokarst forms

Rozwój form krasowych na tle ewolucji geologicznej trzonu paleozoicznego Gór Świętokrzyskich (PcŚM). Numery – stanowiska zgodnie z figurą 1, duże litery – obiekty na figurach 2 i 8, cyfry łacińskie w nawiasach – grupy form krasu kopalnego

<table>
<tr><th colspan="2" rowspan="2">Stratigraphy, lithostratigraphy</th><th colspan="2">General geological processes</th><th rowspan="2">Karst and other denudational forms (numbers and letters = sites)</th><th rowspan="2">Karst fills (numbers and letters = sites)</th></tr>
<tr><th>endogenic processes</th><th>processes on surface</th></tr>
<tr><td colspan="2">1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="2">Triassic – Röt, Lower Muschelkalk</td><td>subsidence progressing eastward, local faultings and uplifts</td><td>marine deposition in the west and central part of PcŚM, local emergency of horsts</td><td>conduits and shafts in eastern part of PcŚM and in emerged tectonic block in the west part of it (IX): 9, 3</td><td>thin-bedded limestone with dolomite and gypsum crystals (IX): 9,
breccia, bedded limestone (IX): 3</td></tr>
<tr><td colspan="2">Triassic – Middle Buntsandstein</td><td rowspan="2">subsidence progressing eastward and east-southward, local faultings and eathquakes</td><td rowspan="2">terrigenous sedimentation of allogenic material at least in the west part of PcŚM</td><td rowspan="2">clastic dykes (6)</td><td rowspan="2">sandstone (in clastic dykes)</td></tr>
<tr><td rowspan="2">Triassic – Lower Bunt-sandstein</td><td>Zagnańsk Fm</td></tr>
<tr><td>Szczuko-wice Fm, (Jaworzna Fm, Siodła Fm)</td><td>tensional disintegration of blocks and their gradual subsidence (lowering) in the west and north segments of PcŚM – faulting, opening of crevices, frequent earthquakes</td><td>terrestial sedimentation (sebkha, lakes) of detrital, mainly allogenic material progressing from foreland of PcŚM eastward and east-southward; denudation of relatively uplifted blocks of the central part of PcŚM;

marine ingression reaching north-western part of ŚM</td><td>d) traces of karst dissolution in tectonic fissures (clastic dykes), karst-sinkholes (chambers?)-(VIII): 4 (J), 7 (N);
c) tectonically conditioned slopes shaped by denudation: valleys, landslides, karrens, potholes (VII): 4 (H, I, J), 10?;
b) “large lenses” – low chambers of large horizontal size (VI): 4 (D, E, F, G), 5;
a) subsurface conduits (V): 4 (C & others)</td><td>d) sandstone – mainly lithic arenite (VIII): 4 (J), 6?,7 (N);
c) mega-conglomerate, breccia, claystone; mudstone to pebble sandstone (VII): 4 (F, G, H, I, J), 10?;
b) sandy limestone, conglomerate, sandstone (VI): 4 (D, E, F, G),5;
a) sandy limestone with fibrous or “cauli-flower” structure (V): 4 (C & others), 5</td></tr>
<tr><td colspan="2">Upper Permian – Zechstein (PZ2-PZt?)</td><td>slight periodical tectonic movements; slight hydrothermal processes</td><td>in places denudation, karstification, local sedimentation of autogenic material</td><td>b)–c) pipes and subsurface conduits, occasional chambers (III and IV): 4 (A), 7 (F, G, I, J, K, L, M)?, 8, 10?;
a) possibly karst dissolution of the tectonic fissures (II): 12?, 13?, 16?</td><td>c) chemically precipitated limestone, marl, claystone, occassionally calcite “różanka” (IV): 4 (A) 5, 7 (F-M), 8, 10?;
a)–b) calclithites as described below (II and III): 4 (B); 12?, 13?, 14?, 15?, 16?</td></tr>
<tr><td colspan="2">(Carboniferous) Permian – Rotliegend, Zechstein (PZ1?)</td><td>tensional movements – faultings and shifts of the tectonic blocks, frequent earthquakes and openings of crevices, intensive hydrothermal processes</td><td>mainly mechanical denudation of the tectonically-morphologically elevated elements, in places (local basins) marine or terrestial sedimentation</td><td>c) potholes, subsurface chambers and passages (III): 4 (B), 12, 14, 15;
b) karst dissolution of the tectonic fissures (II): 12, 13, 16;
a) karst valleys, dolines (I): 7 (A, B, C, D, E), 11</td><td>b)–c) calclithites – detrital carbonates (sandstone, conglomerate), marl with occasional hydrothermal calcite (III): 4 (B), 12, 13, 14, 15, 16;
a) breccia, mega-breccia, occasionally calcite “różanka”, residual breccia (I): 7 (A, B, C, D, E), also limestone, marl: 11</td></tr>
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