Kras i Speleologia

Tom 12 (XXI)

WYDAWNICTWO UNIWERSYTETU ŚLĄSKIEGO
KATOWICE 2008

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i Speleologia

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UNIWERSYTETU
ŚLĄSKIEGO

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Adres redakcji oraz wymiany (Editor's address and address for exchange)
Katedra Geomorfologii, Uniwersytet Śląski
ul. Będzińska 60, 41-200 Sosnowiec
Poland

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Editorial

11 (XX) volume of "Kras i Speleologia", issued in December 2005 by the University of Silesia, was the last one edited by late Professor Marian Pulina (1936–2005). Since 1977 he was the Editor-in-chief and governed the Editorial Staff of "Kras i Speleologia". Special volume dedicated to his memory as well as to his favorite topics of karstology and speleology – cryokarst and karst in polar regions is edited now.

Since last issue of "Kras i Speleologia" Polish and international speleology lost two important members – palaeozoologists working with fossils of cave mammals – Professor Teresa Wiszniowska (1942–2006) from the University of Wrocław and Professor Kazimierz Kowalski (1925–2007) from Polish Academy of Sciences (PAN) and Polish Academy of Arts and Sciences (PAU) in Kraków. Sad message about death of Professor Kazimierz Kowalski has reached in moment of giving the volume for printing.

We present to readers next, 12 (XXI) volume of "Kras i Speleologia", prepared by Editorial Staff being in transition to new one after death of Professor Marian Pulina. This issue contains six papers on morphogenesis and speleogenesis of gypsum karst, cave morphology and cave minerals, as well as regional and applied hydrogeology in karst terrains. According to agreement between members of the international journals on karst and cave science "family" World Karst Science Reviews will be published in each next issue. This part of "Kras i Speleologia" contains contents of recent issues of the international cave and karst journals. Contents of archival and the most recent issues (some of them are full papers on-line) of this "family" readers will find on the new established web sites of the international interests: **http://www.network.speleogenesis.info/index.php** and **http://www.karstportal.org/public/index.cfm** as well as at **http://www.speleogenesis.info/index.php** which has been the precursor of the international internet exchange of karst and caves knowledge.

Artykuły naukowe
Scientific papers

„Kras i Speleologia". T. 12 (XXI). Katowice 2008
Prace Naukowe Uniwersytetu Śląskiego nr 2537

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Caves in gypsum of the Southern Poland and the Western Ukraine – a comparison

Abstract: Cave in the Miocene gypsum rocks of the Carpathian Foreland occurring in Poland (mainly in the Solec area) and in the Western Ukraine (the Podolia and Bukovyna) differ in many features: size, contours and shapes of passages, occurrence in the gypsum strata sequence, hydrological situation, cave deposits, etc. The main reasons of these differences are: 1) different hydrological properties of strata overlying and underlying the gypsum strata, 2) dissimilarity of jointings, which are genetically conditioned, 3) different lithology (structure) of the gypsum rocks. These factors stimulated different hydrological and morphological evolution of the Polish and Ukrainian regions, what consequently caused dissimilarities in karst development. Ukrainian caves were formed mainly due to deep, arthesian water circulation in phases of intrastratal and subjacent karst development, whereas caves in the Solec area (Poland) were formed mainly in water table zone, which has been relatively stable owing to lithologic-tectonical structure of the gypsum strata and their substratum.

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Introduction

Intensive karst process has developed in the Miocene gypsum deposits of marine basin of the Carpathian Foreland. Caves in the gypsum of Polish part of the basin are concentrated in the Solec Trough (microregion called "Solec area" hereafter) representing small fragment of the Nida Basin, whereas the famous and the most interesting caves in the gypsum of the Ukraine are located in the areas of Podolia and Bukovyna (Fig. 1).

Fig. 1. Location of the regions described in the article

Despite of development in the gypsum deposited simultaneously in the same basin (Peryt et al., 1998) Polish and Ukrainian caves represent quite different types. Comprehensive investigations of Ukrainian caves (Andrejchuk, 1988; Klimchouk, Andrejchuk, 1988; Klimchouk, 1990, 1991, 1996) and inventory of the caves in the Nida Basin completed not long time ago (Gubała, Kasza, Urban, 1998; Urban, Gubała, Kasza, 2003) allow to discuss the problem of these differences.

Geological and geomorphological settings

On the Solec area the gypsum strata are often outcropped at the surface. In places they are overlaid by the Upper Badenian claystones of Pecten Beds or directly by the Lower Sarmatian clays of Krakowiec Beds. Occasionally they are covered by thin blankets of the Quaternary sediments (Fig. 3). To the north of the Solec Trough, on the Szaniec Upland they are overlaid by claystones of the Pecten Beds or directly by the Lower Sarmatian which here laterally grades to clastics-carbonate sands and conglomerates. To the east, on the area of the Połaniec Trought, the gypsum strata are underlaid by detrital rocks of the Baranów Beds and overlaid by the Upper Badenian – Lower Sarmatian claystones and marls. The gypsum rocks are partly replaced by sulphur bearing limestones here (Łyczewska, 1972 a, b; Rutkowski, 1986; Krysiak, 2000).

The Solec area is featured by hilly relief with some chains of hillocks and natural escarpments. The chains of hills and quests are usually formed of the "szklica" gypsum, which are relatively well resistant to erosion and protect underlying soft marls agains denudation. Upper part of the hills are elevated up to 50 m above the Nida river valley, which delimits the region from the south-west (Cabaj, Nowak, 1986).

Some 100 caves and rock shelters have been listed in the Solec area and its nearest surroundings; about 80 ones are accessible now. Majority of the caves (rock shelters) are concentrated in a few sites: Skorocice karst valley (26 caves), Aleksandrów karst valley (12 caves), Siesławice (13 caves), Skotniki Górne (5 caves) (Gubała, Kasza, Urban, 1998). These sites are located not far from Nida river valley, less than 35 m above its current level (Fig. 3).

Numerous surface karst forms occur also to the north of the Solec area, on the Szaniec Upland and to the east – on the Staszów area of the Połaniec Trough, but only a few small caves have been found in these regions. Karst of the Szaniec Upland and the Staszów area has developed in the gypsum rocks covered by Miocene claystones or detrital rocks, thus only surface forms reproduced in these rocks are accessible there (Flis, 1954; Liszkowski, 1979; Rutkowski, 1983; Nowak, 1987; Gubała, Kasza, Urban, 1998).

Gypsum rocks in the Podolian area of the Western Ukraine are underlaid by the Miocene detrital quartz rocks and carbonate rocks and overlaid by thin but continuous layer of the carbonate rocks of the Ratynsky Limestone. The gypsum rocks sequence is 15–40 m thick and divided into three zones (Fig. 2 B): a) micro- and fine-crystalline, stromatolitic gypsum of equigranular structure (zone I – 6–8 m thick), b) layer of dome-like structures ussually 1–1,5 m in diameter, formed of macrocrystalline gypsum (zone II – 2–3 m), c) zone of vertically elongated large dome-like structures, 8–10 m in diameter, formed of coarse-crystalline gypsum (zone III – 8–10 m).

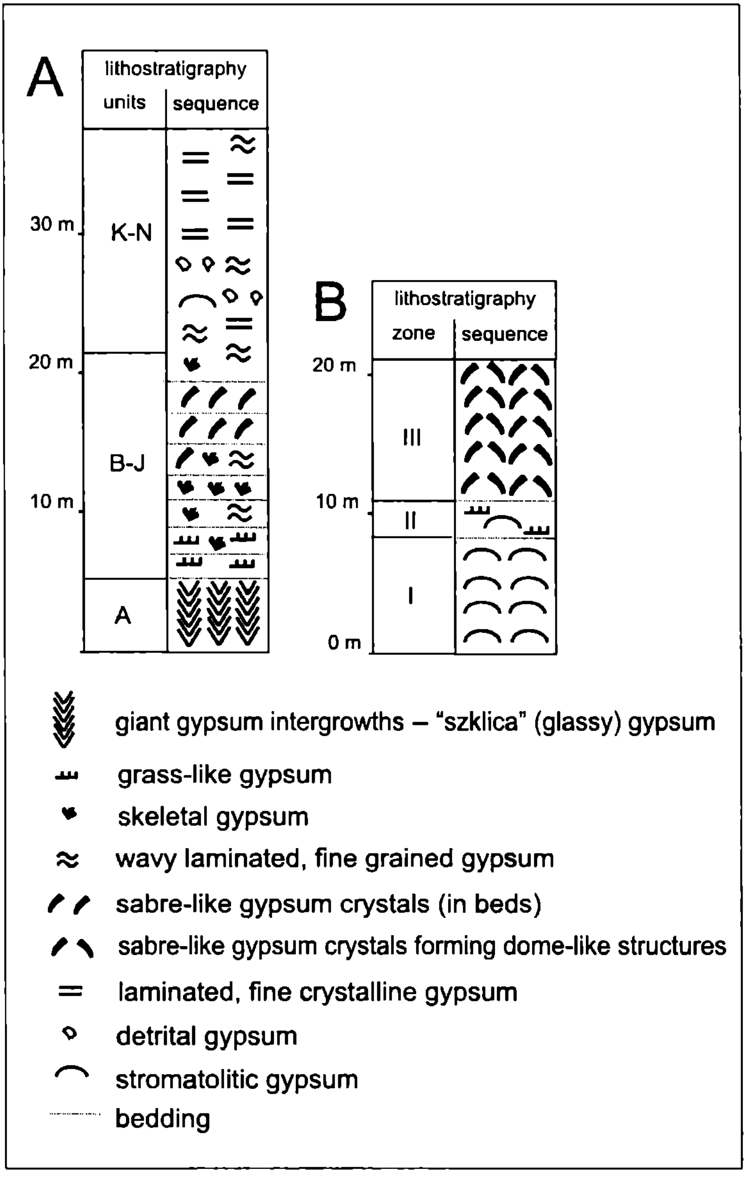


Fig. 2. Gypsum rocks sequences in
A – the Solec area, the Nida Basin, Poland (example from Gacki open pit, after Kasprzyk, 1993, simplified), and B – the Podolian area, the Western Ukraine (example from Optimistychna cave after Klimchouk, Andrejchuk, Turchinov, 1995)

Some thin interbeddings or aggregates of argillo-sulfate and argillaceous rocks occur in the sequence. The most apparent, usually 5–10 cm thick layer of bentonite forms lithological boundary between II and III zones. The structures of gypsum are considered to form during late diagenetical recrystallization due to interstitial water migration. Characteristic systems of tensional joints – different in each zone – are also referred to late diagenetic (katagenetic) processes (Klimchouk, Andrejchuk, Turchinov, 1995; Turchinov, Andrejchuk, 1995).

Gypsum sequence in Bukovynian area differs from the Podolian area. The zone II is represented by laminated gypsum with interclations of micro-and crystalline types. In the uppermost, III zone gypsum crystals are finer and do not form regular dome-like structures.

The Podolia of the Western Ukraine is situated north of Dnister valley and represents uplant dissected by valleys of some Dnister tributaries. More than 50 caves have been registered there. 9 caves longer than 1 km are located in narrow belt of hills parallel to Dnister valley, between valleys of Dzhurin and Zbruch creeks.

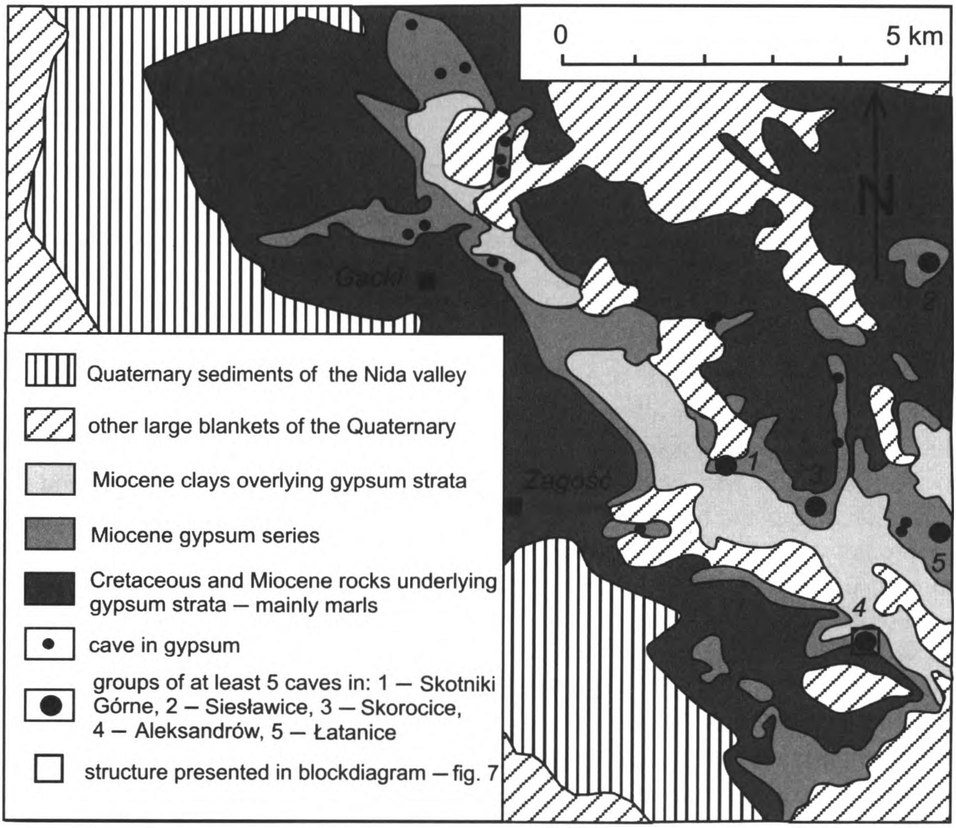


Fig. 3. Geological map of the "Skorocice syncline" (after Łyczewska, 1972a, simplified and modified) covering north-western part of the Solec area with location of the caves

Two others large caves are situated 15–20 km to the north. The Bukovyna is situated between Dnister and Prut valleys, to the south of the Podolian area. It is also hilly, watershed area. In this subregion some 60 caves have been known, among them three are longer than 1 km.

Apart of the Podolian and Bukovynian areas, caves in gypsum rocks of the Western Ukraine are situated first of all in the Pokutsky area to the north-west of the Bukovyna and to the south of the Dnister valley. More than 30 caves in the gypsum have been found there, but that subregion is still not enought eksplored.

Cave features

The main features of the caves in the Podolian and Bukovynian areas and the Nida Basin are characterized below.

Lenght, contours

Caves in the gypsum of the Nida Basin do not exceed a few hundred meters. The longest is Skorocicka Cave (0,35 km), which represents practically one straight passage connecting upper (blind) and lower segments of Skorocice Karst Valley. Four others caves are longer than 0,1 km, 55% of registered caves (rock shelters) are no longer than 0,01 km (10 m). Generally Polish caves represent single or poorly branched passages, as well as irregular, usually low chambers with short galleries in the sides (Fig. 3 A). The conduits follow rare joints of different directions as well as bedding planes. Several secondary caves formed due to breakdowns of karst cavities are also observed. Directions of the caves in Skorocice and Aleksandrów are nearly parallel to surface karst forms and to extension of gypsum beds. Exceptional is only Sawickiego Cave, which represents simple network of tubular passages formed along joints developed near the fault zone (Gubała, Kasza, Urban, 1998; Urban, Gubała, Kasza, 2003).

Fourteen caves in the gypsum in the both areas of the Western Ukraine described above are longer than 1 km. Among them are the longest caves in gypsum of the world: Optimistychna (208 km), Ozerna (117 km) and Zoloushka (Popelushka) caves (92 km). Caves Mlynky (24 km) and Kryshtaleva (22 km) exceed 10 km, too. Ukrainian caves represent maze systems of galleries developed along networks of vertical or steeply inclined joints (Fig. 3 B). The network patterns are controlled by joint systems, which are different in each of three zones occurring usually in the gypsum sequence. In the lower and middle zones (I and II) of the gypsum sequence they are crossed in two perpendicular directions forming mainly quadrangular polygons and 4-beam junctions, whereas the joints in the upper (III) zone they often form polygonal network with predomination of 3-beam junctions (Klimchouk, 1991, 1996; Klimchouk, Andrejchuk, Turchinov, 1995).

Ukrainian long caves are divided into several "regions" and "subregions" – integrated network of conduits, which represent microblocks delimited often by tectonic zones. Networks of cave passages in particular "regions" are almost uniform and do not change towards the borders. Lateral extends of the caves are small in relation to their total lenghts, what is expressed by high densities of karst cavities and coeficients of karstification (Klimchouk, 1991, 1996; Klimchouk, Andrejchuk, Turchinov, 1995).

Vertical development

Majority of Polish caves are developed horizontally. Vertical amplitude does not extend 10 m, usually is less than 5 m. Caves are developed almost exclusively on one storey, although some passages are relatively high. These high caves represent underground stream channels, which have been downcut due to corrosional and erosional activity of water streams related to gradual lowering of water table. It is documented by relics of one or two levels of stream beds above current water table in some caves in Skorocice (Głazek, 1993; Głazek, Harton, Wicik, 1994; Urban, Gubała, Kasza, 2003) – Fig. 4.

Rare vertical caves are represented with systems of crevices developed (widened) above collapsed karst cavities, which were formed near the underground water level (Ucho Olki cave in Skorocice). Vertical shafts of dissolution or dissolution-erosional origin are rare among caves of the Solec area (Urban, Gubała, Kasza, 2003). Typical small but numerous dissolution shafts on the gypsum rocks surface are observed in the Szaniec Upland (Chwalik et al., 2002).

Vertical amplitude of the 14 largest caves of the Podolian and Bukovynian areas varies between 10 m and 30 m. The large caves consist usually of two or three horizons referred to different structural gypsum zones. The horizons are usually (but not always) developed in separated, neighbouring "regions" and connected by single passages but. In some caves development of cave horizons by waters ascending from lower ones is well documented. In Atlantyda, Dzurinska and Ozerna caves the upper storeys are even not continuous and they developed due to direct upward expansion of karst cavities from particular elements of the lower level (Klimchouk, 1990, 1991, 1996; Klimchouk, Andrejchuk, Turchinov, 1995). Characteristic features of the Ukrainian caves are vertical trough structures (VTS) – breakdown structures induced by gypsum dissolution, propagated upward often by breakdowns and filled (or partly filled) by debris of rocks occurring in their uppermost part or overlying gypsum rocks. Their formation started often during main phases of karst development and facilitated hydraulic communication between karst levels (Klimchouk, Andrejchuk, 1996).

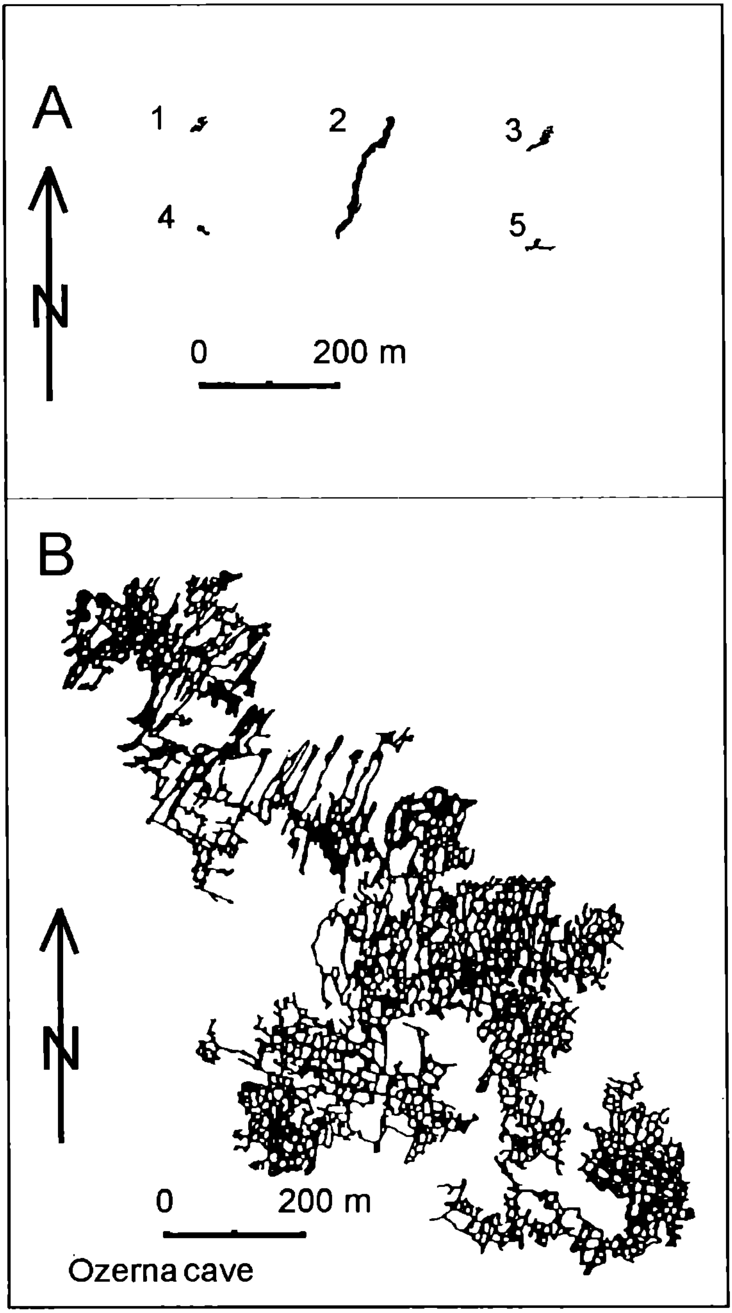


Fig. 4. Typical cave contours in
A – the Solec area; 1 – Szeroka Cave, 2 – Półkolista Cave, 3 – Skorocicka Cave, 4 – Sawickiego Cave, 5 – Aleksandrów Cave; B – Podolian and Bukovynian areas

Occurrence in the gypsum sequence and lithological control of the caves shape

Although in the Nida Basin karst corrosion has developed in the whole gypsum sequence (what is documented in open pits Leszcze and Stawiany – see Nieć, Uberman, 1998), cave occurrence is determined by gypsum structure and mechanical properties. In the Solec area 75% of the caves are situated in skeletal and sabre-like gypsum of the middle section representing nearly half of the thickness of the gypsum sequence (Urban, Gubała, Kasza, 2003). They are represented mainly by tubular (round or oval in cross-section), semi-oval (arch-like), occasionally lenticular – high or low – horizontal passages as well as dome-like or irregular chambers. Bedding is an important factor controlling the shape of caves in this gypsum type (section). It is responsible for some low (horizontally extended) cavities (passages, chambers) ultimately shaped by breakdowns of gypsum beds. Shape of some high (vertically extended) passages are determined by downward entrenchment of underground water streams (Turchinov, 1997; Gubała, Kasza, Urban, 1998).

Relatively high number of caves (some 20%) occurs in the "szklica" gypsum – the lowermost layer of gypsum rocks sequence. They are represented mainly with: a) vertical karst crevices and triangular, rhomb-like or oval forms developed along rare straight (tectonic) joints, b) low, horizontally expanded cavities in the bottom of the gypsum strata (directly on top surface of the underlying marls). Karst cavities in the "szklica" gypsum are very stable and do not undergo mechanical destruction before reaching overlying bedded gypsum (Turchinov, 1997, Gubała, Kasza, Urban, 1998; Urban, Gubała, Kasza, 2003). Several forms developed just in the boundary between "szklica" and bedded gypsum occur in Skorocice Valley.

Karst cavities in detrital and microcrystalline, laminated gypsum of upper section are relatively rare, their number does not exceed 5% of all listed caves. Dissolution is not slower in these rocks but karst cavities are quickly modified and filled with debris fallen down due to very low mechanical resistance of the gypsum. A few caves mainly oval or lenticular in cross-sections were observed in laminated gypsum (Urban, Gubała, Kasza, 2003).

In the Western Ukraine caves occur in all three zones of the gypsum sequence, but particular horizons of cave passages are restricted (confined) to each lithological zone. Optimistychna and Ozerna caves are constituted of three storeys of galleries which are developed in three zones of the gypsum rocks sequence, but caves with conduits formed on two storeys are also frequent. In some caves (Ozerna, Dzurinska, Atlantyda) one storey is characterized by existence of master conduits, whereas other represents subordinate and partly discontinuous karst systems (Klimchouk, Andrejchuk, Turchinov, 1995; Turchinov, 1997).

In the lower (I) lithological zone of the gypsum sequence prevail fissure-type, lenticular and rhomb-like galleries as well as low, horizontally extended cavities, which occur in the bottom of the gypsum strata. The middle (II) zone is characterized by ussually smaller quadrangular, rectangular or triangular cavities. The shape of ceilings of these forms is often controlled by layer of clay (bentonite) situated in the top of the zone (Klimchouk, Andrejchuk, Turchinov, 1995; Turchinov, 1997).

Cavities in the upper (III) zone of Ukrainian gypsum sequence are featured by very various shape. Conduits of vertically expanded lenticular, rhomb-like and triangular cross-sections were formed along joints. But specific forms of this zone are passages and chambers developed due to dissolution and breakdowns of dome-like gypsum structures: cupolas and half-spherical cavities with secondary shelves, niches, ridges as well as collapsed blocks ("stone balls" etc.) (Klimchouk, Andrejchuk, Turchinov, 1995; Turchinov, 1997).

Generally in Polish and Ukrainian gypsum karst regions described here shape of the cave passages are controlled by gypsum structure, their susceptibility for dissolution and mechanical properties. Thus shape of the passages can be similar in some places, but more differentiated structure of Ukrainian gypsum rocks, especially common occurrence of giant dome-like structures in the upper (III) zone causes that the forms of cavities are more diversified. Characteristic feature of Ukrainian caves are also corrosional forms developed upward due to water circulation in phreatic zone as well as vertical through structures (VTS), which are practically absent in Polish caves.

Hydrological situation of the caves

In the Solec area majority of caves are situated very close to underground water table. Caves –77%, are situated less than 2 m above water table. Ponds or streams occur in 40% caves. Only 11% caves are totally drained, situated in upper parts of hills, more than 5 m above water table (Gubała, Kasza, Urban, 1998; Urban, Gubała, Kasza, 2003).

Almost all caves longer than 1 km of both Podolian and Bukovynian areas are situated in drainage zone, above underground water table now. The subsurface lakes occurs only in Zoloushka (drained due to anthropogenic activity – quarrying and consequent water table lowering), Ozerna and Optimistychna caves, but despite of that the uppermost segments of these caves are elevated almost 20 m above underground water table (Klimchouk, Andrejchuk, 1988; Klimchouk, 1990, 1991, 1996; Klimchouk, Andrejchuk, Turchinov, 1995).

Secondary mineral forms in the caves

In Polish caves predominate secondary mineral forms of gypsum and calcite precipitated from water solutions (seeping into subsurface cavities) owing to evaporation or CO_2 degassing. The most common secondary aggregates are gypsum incrustations of various shape: "beads", "grapes", "mushrooms", "bushes" forming covers up to 1–3 cm thick, which are developed on cave walls and ceillings in better ventilated (faster dried) segments of the caves (near the entrances). Small and irregular stalactites formed of calcite or calcite-gypsum intergrowths have originated on ceilings where the water percolation has been more intensive. Rare microcrystalline gypsum sheets with smooth, kidney-shaped surfaces are supposed to be related to biochemical processes (Kasprzyk, Urban, 1996; Gubała, Kasza, Urban, 1998).

In Ukrainian caves spectrum of secondary mineral forms are much more diverse, although forms genetically similar to ones known in Polish caves are common. Gypsum incrustations and crystal aggregates prevail on cave walls and ceilings: rose-like forms, anthodites, "neddles", "grapes", helictites etc. Calcite speleothems are represented by dripstones (stalactites and stalagmites), flowstones (drapperies etc.) as well as helictites and rhomboedral aggregates. Calcite-gypsum intergrowths, e.g. calcite spherolites are frequent, too. Subaquaeous calcite forms – crusts, rafts, dumps, pisoides etc. – occur in cave ponds. To the most interesting belong "gypsum snow" – loose aggregates accumulated on passage floors or covering cave walls. They are interpreted as forms of crystallization from aerosols (Turchinov, 1999).

Apart of gypsum and calcite in Ukrainian caves secondary celestine (needle and flake-like aggregates in gypsum), rodochrosite, chalcedone as well as iron oxides (irregular concentrations, stalactites and stalagmites) have been observed (Turchinov, 1999).

Mechanical cave deposits

Caves of the Solec area in Poland are often devoid of mechanical sediments (except of gypsum debris fallen down from ceilings), since they have been washed away by water streams. In some caves accummulations of black soil-gypsum rendzina – occur (Gubała, Kasza, Urban, 1998). This soil was transferred to the caves after deforestation of the area in the Middle Ages (Głazek, 1993). In two caves sands and clays with remnants ofthe Quaternary fauna were observed (Kowalski, 1954). Remnants of the deposits directly overlying gypsum strata (Miocene claystones) have not been found in the caves of the Solec area (Gubała, Kasza, Urban, 1998).

In Ukrainian caves predominate clays and silty clays formed of material originated from strata overlying the gypsum rocks. They are usually fine grained and well sorted what document their sedimentation during late stages of artesian speleogenesis. Sands and gravels represent younger sediments, which have been accumulated near shafts and ponors connecting caves with surface. Gypsum blocks and debris formed due to breakdowns are also common (Klimchouk, 1991, 1996).

Discussion – the reasons of differences between Polish and Ukrainian caves in gypsum

Presented above differences between caves in gypsum rocks of Poland and the Western Ukraine are caused by conditions of gypsum occurrence and factors controlling karst development. The main of them are described below.

Different hydrogeological properties of the strata underlying and overlying the gypsum series

Hydrological properties of the rocks underlying and overlying gypsum series were essential factors controlling water inflow to gypsum strata during artesian phase of water circulation (because gypsum is rather poorly permeable medium, when it is yet not karstified – Liszkowski, 1979; Klimchouk, 1990, 1991; Klimchouk, Andrejchuk, 1996; see also Lowe, Gunn, 1997). In the Western Ukraine under and above gypsum occur strata of carbonate and partly detrital quartz deposits. Both horizons represented relatively permeable rocks during artesian water circulation: the lower stratum – as detrital rocks characterized by original sedimentary-diagenetic porosity, the upper one – as chemogeneous rocks genetically related to water circulation. It facilitated water supply to the gypsum rocks.

In the same stage of geological evolution gypsum strata of the Solec area in Poland were at least partly isolated from fresh, meteoritic water inflow by overlying Miocene claystones and underlying Miocene and Cretaceous marls. Cretaceous marls are well fractured and permeable only in tectonic zones (Łyczewska, 1972a; Dynowska, 1983).

Different joint systems in the gypsum rocks

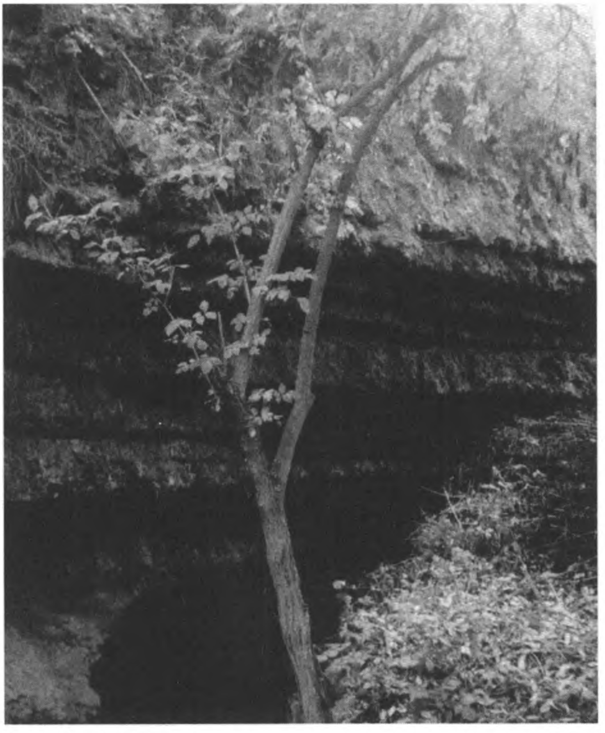
Since poor permeability of gypsum (before karstification), system of joints and/or bedding planes seems to be the main factor controlling water circulation in the early (inception) stage of speleogenesis in the gypsum rocks. It represents the main element governing scale and type of karstification. Thus difference of jointing patterns between Ukrainian and Polish gypsum rocks is the essential factor determining dissimilarities of countours of the caves.

The gypsum rocks of the Podolian and Bukovynian areas were strongly transformed (recrystallised) during late diagenesis, what resulted in formation of systems of lithogenetic, tensional joints. These vertical joints are usually independent from directions of tectonic stresses and form dense but different polygonal networks in each lithological (described above) zone of the gypsum sequence. Existence of these networks considerably facilitate water circulation in the particular zones as well as – in some places – connection between the zones. This connection is also possible along tectonic fractures, which are more frequent to the south. In the Bukovynian area, situated closer to the Carpathians, a role of tectonic fractures is more significant, even decisive in speleo-network formation. According to the recent investigations (Klimchouk, Andrejchuk, Turchinov, 1995; Klimchouk, 1996) diffusional flow during artesian water circulation between two limestone aquifers underlying and overlying gypsum strata resulted in development of karst in the gypsum.

The gypsum rocks of the Solec area have not undergone to more advanced diagenetical transformations preserving their sedimentary (or early diagenetic) structures (Kasprzyk, 1993; Bąbel, 1999). In the upper part of the gypsum sequence karstification could have been stimulated by original (sedimentary) porosity developed due to brecciation, which is related to phases of depositional karst (emergences and breaks of sedimentation – Bąbel, 1999) and due to immediate postdepositional karst (see Osmólski, 1976, Krysiak, 2000)[1]. In the grass-like, skeletal and sabre-like gypsum of the middle section of the gypsum sequence (about half of its total lenght) apparent sedimentary bedding (Phot.1) was the main factor controlling water circulation and – in consequence – karst development. Vertical joints are poorly developed in this middle section of gypsum sequence as well as in the clastic gypsum of the upper part of the sequence, in which occur only fissures of tectonic nature, frequent only near faults. System of vertical

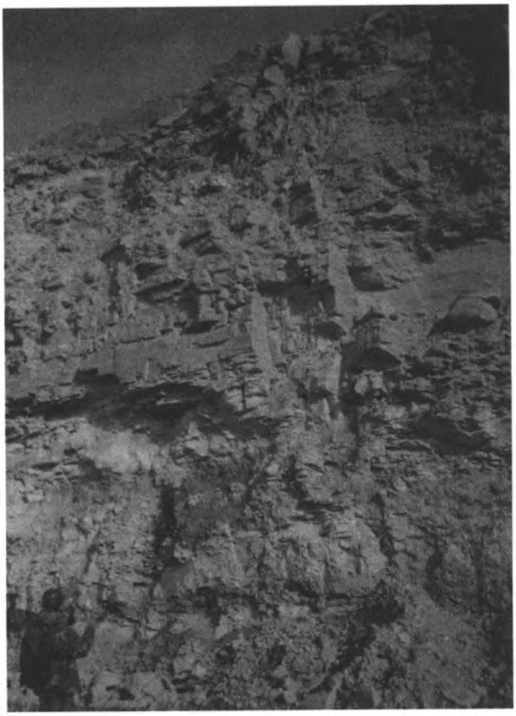
[1] Out of the Solec area described in the paper, in the eastern part of the Nida region (and whole Miocene basin) the essential factor stimulating water circulation and karstification was gypsum alteration and replacement by sulphur bearing limestones (Piątkowski, 1974; Osmólski, 1976 and others).

joints (might be of diagenetical origin, similar to Ukrainian ones) is observed only in the microcrystalline units of upper part of the sequence, but traces of karstifications along the joints surfaces are observed sporadically (Phot. 2). In the lowermost unit of the "szklica" gypsum irregular network of microfissures separating giant crystals are observed, but its role in speleogenesis seems to be insignificant.



Phot. 1. Sedimentary bedding of sabre-like gypsum of the middle section of the series in the Nida Basin – Skorocice valley, gypsum wall above the entrance of Jaskinia z Potokiem cave (photo by J. Urban)

Occurrence of bedding planes in slightly inclined gypsum strata ought to favour horizontal water flows, parallel to rocks extension in the zone situated close to water table. Active flows in this zone should stimulate fast formation of horizontal karst conduits along the bedding planes (Flis, 1954), not only due to dissolution, but due to mechanical erosion, as well. Karst conduits developed concordantly to beds extension are common in Skorocice Valley and Alexandrów (Urban, Gubała, Kasza, 2003), what indicates that the gypsum rocks were intensively karstified during shallow phreatic phase of (hydro)geological evolution.



Phot. 2. Rectangular jointing in the microcrystalline, laminated gypsum of the upper section of the series in the Nida Basin – Leszcze quarry (photo by J. Urban)

Different gypsum lithological sequence

Different mechanical properties of the gypsum rocks of the sequences in Polish part of Miocene basin and Ukrainian Podolia and Bukovyna are important factor controlling evolution of the karst forms in mature stage of their development as well as morphogenesis of gypsum rocks (and their overburden) surface.

Upper zone of the gypsum in the Podolian and Bukovynian areas is formed of the coarse-crystalline gypsum rather resistant to mechanical (gravitational) stresses. It resulted in prolonged preservation of underground karst cavities, representing deep, intrastratal karst (formed during artesian stage of speleogenesis – see above), in shallow phreatic conditions and subsequently, in vadose, drained zone. In consequence morphological evolution (denudation) of the Earth surface – formed directly by the gypsum rocks or still by their overburden – has been relatively slow, even if some vertical through structures (VTS) have reached the surface. Also limestone cover (Ratynsky Limestone) has played important role in preservation of underground cavities, especially in the Bukovinsky area (A n d r e j c h u k, 1999).

Upper section of the gypsum sequence in the Solec area, formed of the microcrystalline and clastic gypsum has easily undergone mechanical processes, what caused fast evolution – strictly destruction – of underground karst forms, breakdowns and development of surface forms of subjacent karst. These processes accelerated denudation of upper part of the gypsum series and – subsequently – denudation of gypsum overburden. It shortened the period of deep circulation and the existence of phreatic conditions in the upper part of the gypsum of the Nida Basin in comparision to Ukrainian gypsum. Thus the intrastratal phase of karst development in the Podolian and Bukovynian areas was much longer than it could have been in the Solec area owing to fast denudation. Neverthelles the underground kast forms have been preserved in the lower part of the gypsum sequence, because the skeletal and sabre-like gypsum of the middle section and especially lowermost unit of the "szklica" gypsum represent relatively hardly denuded rocks. Shallow phreatic conditions have been able to survive for prolonged time in the lower part of the gypsum strata due to less permeability of the underlying marls.

Different morphological and hydrogeological evolution of the described regions

Dissimilarities in structural situation, diagenesis and lithology of the gypsum strata in the Solec area of Poland and in the Podolia and Bukovyna of the Western Ukraine have brought to different geomorphological and hydrological evolution of these regions and – in consequence – different speleogenesis. These dissimilarities caused that development of the karst forms took place in the different stages of morpho-hydrogeological evolution (Table 1).

In the Podolian and Bukovynian areas deep circulation of artesian water enabled by occurrence of limestone and clastic aquifers under and above the gypsum strata generated intrastratal karst development. This early phase of speleogenesis was considerably enhanced due to existence of the networks of dense joints in the gypsum, what resulted in formation of maze systems of conduits. Therefore this phase represents the main stage of karstification in described areas and caves formed in this time have been preserved up to now (Table 1). Later karst modifications, developed during shallow phreatic and vadose phases were less important in comparision to intrastratal karst, what is conditioned by: 1) the structure and mechanical properties of the gypsum, which have counteracted fast cave breakdowns and extensive denudation of gypsum strata and their overburden, 2) relatively fast evolution of hydrological conditions caused by lowering of water table in the gypsum strata and their substratum after erosional entrenchment of the Dnister and Prut valleys caused by tectonic uplifting of the regions.

Table 1

Phases of karst development in the Solec area, Poland and in the Podolian and Bukovynian areas, the Western Ukraine

Phases of karst development	Southern Poland Solec area	Western Ukraine Podolian and Bukovynian areas
1. Depositional and immediate postdepositional karst	●	●
2. Intrastratal karst	●	●●●
3. Subjacent karst	●	●●
4. Entrenched karst	●●●	●
5. Denuded karst	●●●	

Hydrogeological properties of the gypsum strata and surrounding rocks in the Solec area of the Nida Basin did not favour deep water circulation. The gypsum rocks were rather poorly permeable at the inception stage of speleogenesis (see Lowe, Gunn, 1997), whereas in the marls of the gypsum substratum water flows were limited to fault zones. Therefore intrastratal phase of karstification in the lower and middle sections of the gypsum sequence was probably restricted to development of some initial conduits, which attained larger size only along main faults or if they formed hydrological connections between them. Intensive karstification of the gypsum rocks started in the moment of partial removing of the claystone overburden, when meteoric water directly infiltrated to the gypsum and horizontal flows related to underground water table became active. Lithological properties of detrital and fine crystalline gypsum strata of upper section enabled not only dissolution but extensive mechanical denudation of these rocks and overlying claystones as well as incision into the lower sections of the gypsum sequence in some places. Therefore underground water table fast lowered in the upper section of the gypsum strata, driven by relatively quick denudation and downcut of the river valleys.

The water table has been more stable in the rocks of lower part of the sequence, which are more resistant for denudation. In local tectonic or sedimentary concave structures (as grabens, synclines, troughs, etc.) relative stabilization of the water table has been governed by existence of the impermeable marls in the gypsum basement. Resistant bedded gypsum and especially "szklica" gypsum has protected soft marls against denudation, what has delayed depressing of the water table till the erosional incision into the marls on the limbs of these concave forms. The example of this situation is observed in southern limb of the "Skorocice syncline"[2] (Fig. 3) near

[2] The name "syncline" used by Flis (1954) seems to be rather not adequate for this complex structure and was not used by other authors.

Aleksandrów and Skotniki Dolne, where curved upward upper surface of marls "props up" underground water table in the gypsum strata to the level of denudational entrenchment of marl-gypsum boundary. Local underground water reservoirs of this "syncline" are discharged by overflow springs or underground, cave streams of the same character (Fig. 5) (see also Flis, 1954). Very irregular surface of marls-gypsum boundary of the "Skorocice syncline" (Łyczewska, 1972a, b; Krysiak, 2000), suggests occurrence of numerous local tectonic or sedimentary depressions of this surface, which thus represent local water reservoirs. Level of water table in them has been controlled mainly by the rate of erosion of the gypsum rocks and their substratum in the limbs of the depressions (basins). In consequence the local water table in lower part of the gypsum sequence in the "Skorocice syncline" has been independent to water table in the Nida river valley, even in the time of deep entrenchment of this valley (to the level 130 m a.s.l., some 50 m below present level – Łyczewska, 1972a, b) during the Pleistocene interglacials.

In the middle section of the gypsum sequence horizontal flows in shallow phreatic zone have been facilitated due to (sub) horizontal gypsum bedding (beddind planes were gradually widened owing to karstification). These flows caused development of karst cavities parallel to beds extension and often, but not always, situated on bedding planes (Flis, 1954). Thus, the present caves occurring in lower and middle sections of the gypsum sequence of the Solec area, partly initiated in intrastratal and subjacent karst phases, have been formed mainly in shallow phreatic-vadose transitonal zone during prolonged period of water table lowering (Table 1). This is documented by two or three levels of stream channel downcut in some caves.

Apart of the evident differences, sparse similarities betwen Polish and Ukrainian caves in the gypsum rock can be mentioned. They are represented with some shapes (cross-sections) of the caves, as tubular, lenticular or arch-shape passages, which are conditioned by some similar macrostructures of the gypsum rocks as well as general character of speleogenesis in gypsum. Also similar secondary gypsum and calcite forms are observed in Polish and Ukrainian caves, although in the first ones they are developed in much less scale. It is caused by microclimatic conditions, which are similar in some parts of currently drained caves.

As it was mentioned above, gypsum rocks occur in the marine depositional sequence of the north zone of the Miocene basin. Apart of the Solec Trough they are karstified in some other microregions of the Nida Basin, especially in the Szaniec Upland and the Połaniec Trough (Piątkowski, 1974; Osmólski, 1976; Liszkowski, 1979; Rutkowski, 1983l; Nowak, 1986; Kasza, Gubała, Urban, 1998). It is very likely that different geological structures and litological circumstances in these microregions stimulated development of partly or quite other kinds of karst forms.

The main factors controlling karst development in these microregions have been: a) occurrence of detrital (and consequently porous) Baranów Beds as the gypsum substratum, b) higher permeability of the upper part of the gypsum

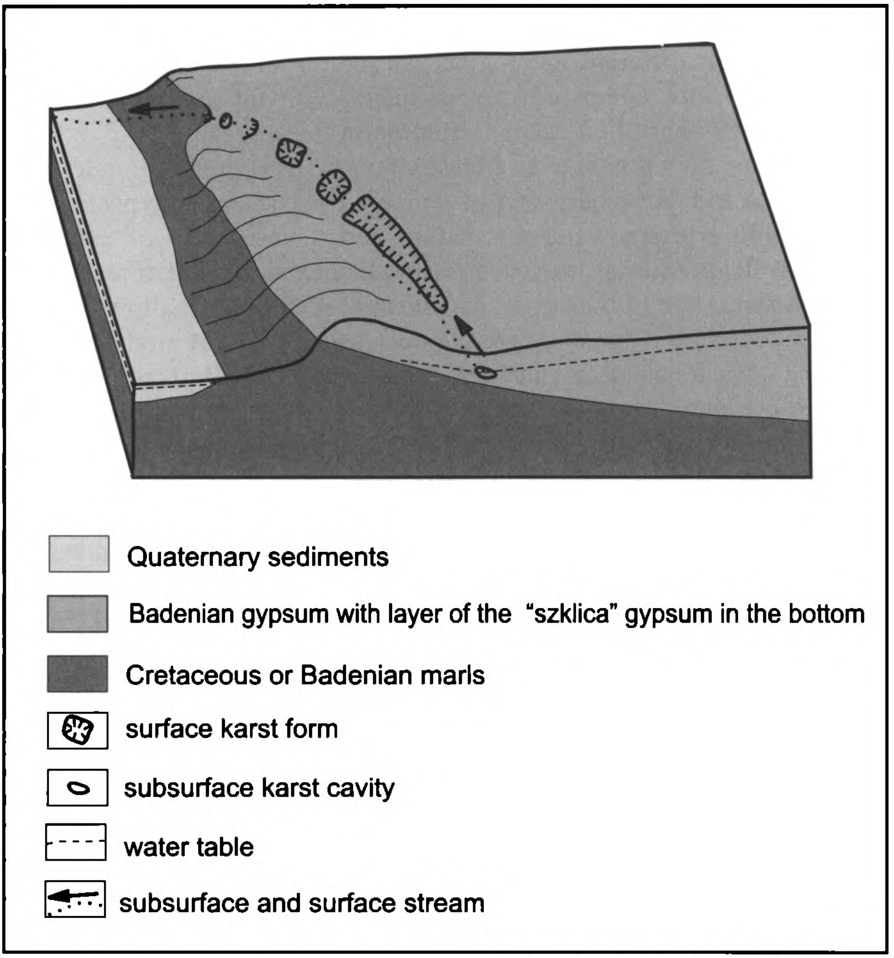


Fig. 5. Blockdiagram of the southern limb of the "Skorocice syncline" in Aleksandrów, Nida Basin – the water table within the syncline is controlled by incision of the stream valley into the gypsum rocks and their substratum in the limb of the syncline

strata caused by brecciation and syndepositional or immedately postdepositional karstification, which subsequently stimulated gypsum alteration to sulphur bearing limestones on this area (Osmólski, 1976), c) subsequent occurrence of sulphur bearing, cavernous limestones, d) various lithology of rocks overlying gypsum strata. These factors favoured formation of karst conduits more similar to the longest Ukrainian caves, but they are generally not accessible now, perhaps partly fossiled (collapsed, filled by sediments) or not opened to surface.

Conclusions

Numerous dissimilarities between caves in the Solec area of the Nida Basin, Poland and caves in the Podolia and Bukovyna areas, Western Ukraine are the effects of different geological structure and geomorphological evolutions of the both compared regions. The following particular factors and processes have controlled caves formation in these areas:

1. Permeability of the carbonate and clastic layers overlying and underlying gypsum strata and dense networks of joints in the Ukrainian gypsum rocks made possible artesian water circulation and development of extensive conduits systems during early, intrastratal phase of karstification. It resulted in formation of the caves, which subsequently, in shallow phreatic and vadose conditions have undergone only less important modifications.
2. Marls and claystones occurring under and above gypsum strata in the Solec area prevented these rocks from intensive deep circulation of water and formation of karst system before direct inflow of meteoric water to the gypsum connected with (partial) denudation of overburden. Therefore caves in the rocks developed mainly during late stages of karstification in the shallow phreatic conditions near to the level of unconfined water table.
3. Systems of late diagenetic (lithogenetic) joints are the main factors controlling contours and shape of the Ukrainian caves (especially in Podolian part of region), whereas lack of dense jointing in the lower and middle sections of the gypsum sequence in Poland favoured bedding planes as the ways of karst conduits propagation and – in consequence – their relation to local tectonic patterns.
4. Relatively hard rocks in the upper zone of Ukrainian gypsum sequence have protected large caves from fast denudational destruction, whereas lithology of the upper section of the gypsum strata of the Solec area in Poland favoured fast denudation. Nevertheless occurrence of more resistant gypsum in the middle and lower section of the sequence and hardly permeable marls in their substratum have delayed denudation and caused relative stabilisation of water table in tectonic or sedimentary depressed structures, what has stimulated prolonged and still active evolution of karst systems in the Solec area.

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Jan Urban, Viacheslav Andreychouk, Jacek Gubała, Andrzej Kasza

Jaskinie krasu gipsowego południowej Polski i zachodniej Ukrainy – porównanie

Streszczenie

Jaskinie w mioceńskich gipsach przedgórza Karpat, które występują w Polsce (głównie w obrębie Niecki Soleckiej) oraz w zachodniej Ukrainie (na terenie Podola i Bukowiny), różnią się między sobą wieloma cechami, przede wszystkim rozmiarami i kształtem systemów jaskiniowych (wśród jaskiń ukraińskich występują najdłuższe na świecie jaskinie w gipsach), ale również formą korytarzy jaskiniowych, położeniem jaskiń w profilu skał gipsowych, położeniem w stosunku do zwierciadła wód podziemnych, charakterem osadów jaskiniowych. Głównymi przyczynami tych różnic są: 1) odmienne własności hydrogeologiczne skał występujących w podłożu i nadkładzie gipsów w obu częściach przedgórza, 2) odmienny system powierzchni nieciągłości (spękań i uławicenia), co uwarunkowane jest różnicami przemian diagenetycznych, 3) różna litologia (struktura tekstury) gipsów.

Czynniki te zdecydowały o odmiennej ewolucji morfologicznej i hydrogeologicznej obszarów występowania gipsów w Niecce Soleckiej oraz w regionach podolskim i bukowińskim. Jaskinie Podola i Bukowiny powstały głównie w rezultacie głębokiej, artezyjskiej cyrkulacji wód, na etapach rozwoju krasu śródwarstwowego i zakrytego. Natomiast jaskinie Niecki Soleckiej rozwinęły się w strefie swobodnego zwierciadła wód, położonego niezbyt głęboko pod powierzchnią terenu. Ich rozwój związany był (i jest) ze stabilizacją tego zwierciadła w dolnej części serii gipsowej, co w Niecce Soleckiej jest uwarunkowane litologią i tektoniką gipsów oraz ich podłoża.

Jan Urban, Viacheslav Andreychouk, Jacek Gubała, Andrzej Kasza

Cavernes dans les gypses du sud de la Pologne et de l'ouest de l'Ukraine – a comparaison

Résumé

Les cavernes dans les gypses miocènes du piémont des Carpates, présents en Pologne (surtout dans les alentours de Niecka Solecka) et dans l'ouest de l'Ukraine (sur le terrain de la Podolie et da la Bucovine) se diffèrent par de nombreux traits, avant tout par la superficie et le relief des systèmes de cavernes (les cavernes ukrainiennes comptent parmi les grottes en gypse les plus longues au monde), mais aussi par la forme des couloirs, la position des cavernes dans le profil de gypse, la position par rapport à la surface d'eau souterraine, le caractère des incrustations dans les cavernes. Les raisons principales de ces dissemblances sont: 1) les propriétés hydrogéologiques différentes des roches de la surface et des recouvrements des gypses dans les deux parties du piémont, 2) un système différent de la surface des fissures (crevasses et bancs) ce qui est provoqué par les différences des changements diagénétiques, 3) une lithographie différente (de la structure et de la texture des gypses).

Ces facteurs ont déterminé l'évolution morphologique et hydrogéologique différente des terrains de gypse dans Niecka Solecka et la région de la Podolie et de la Bucovine. Les cavernes de la Podolie et de la Bucovine sont formées comme résultat d'une circulation artésienne profonde des eaux, à l'époque du karst affleurant et couvert. Contrairement les cavernes de Niecka Solecka sont

formées dans la zone de la surface hydrostatique, positionné non profondément sous la surface du terrain. Leur développement était (et l'est encore) lié à la stabilisation de cette surface hydrostatique dans la partie basse de la série du gypse, ce qui, dans Niecka Solecka, est conditionné par la lithologie et la tectonique des gypses et de leur lit.

First received: March 2004.

„Kras i Speleologia". T. 12 (XXI). Katowice 2008
Prace Naukowe Uniwersytetu Śląskiego nr 2537

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Morphology of the Magurska Cave and its genesis as outflow system from Hala Gąsienicowa planation surface

Abstract: A geomorphological map of the Magurska Cave is presented and some speculation on the morphology and present morphogenic processes are discussed. The ideas of Tatra Mountains geomorphological evolution and the origin of the Magurska Cave in Neogene are discussed. There are recorded phreatic, watertable and vadose stages of evolution. The Magurska Cave is considered as a draining system from Hala Gąsienicowa planation surface developed since Neogene. There are distinguished two apparent parts (Hercman, 1991), the older one of big chambers is regarded as the way of previous water path discharged on the contact with the impermeable rocks of the sub-Tatric nappe as a big resurgence in the Jaworzynka Valley, the second one directed water first to the Jaworzynka Valley too (Kicińska, 1996) in NE direction, next to the Kasprowa Valley, to NW. These younger corridors evolved probably during high water table in epiphreatic zone. The older part with big chambers evolved in stable tectonic and climatic conditions of Neogene close to the watertable.

Introduction

The entrance to the Magurska Cave in Tatra Mountains is located in the steep gully dropping from Czuba Jaworzyńska to the Pod Czerwienicą gully

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(Fig. 1, Fig. 2). This cave has been well known for a long time, the results of first research in that cave were published in second half of the 19-th century. Contemporary studies in the Magurska Cave are concerned with geological studies (Hercman, 1986, 1989, 1991; Hercman et al., 1987; Kicińska, 1995, 1996). The problems of morphology and genesis of the cave have been briefly discussed only by Hercman (1991). That's why the author decided to publish the results of the research with the map of cave morphology, made on the background of S. Zwoliński (1955) map of the cave, modified by T. Nowicki (in: Grodzicki, 2002).

The paper is a summary of the author's MSc thesis "Morphology of the Magurska Cave" prepared in Department of Geomorphology, University of Silesia (Pawłowska, 2002), under the supervision of Professor Marian Pulina.

Morphological studies comprise: geological observations and tectonic fissures measurements, geomorphological mapping and microclimatic measurements with observations made to show the range of present morphogenic processes in the dynamic zone of the cave. As the effect of the obtained results and discussions with prof. M. Pulina the Author gave a hypothesis related to the connections between the Magurska Cave development and the evolution of Hala Gąsienicowa planation surface.

Speleogenetic ideas in the Western Tatra Mountains related to the planation surfaces

Analysis of the cross sections of the cave systems in the Western Tatra Mountains shows regularly occurring horizontal levels, which are cut by sometimes very deep shafts. According to known ideas of cave system genesis in Western Tatra Mountains (a.g.Wójcik, 1966; Rudnicki, 1967; Grodzicki, 1991) the horizontal parts of the caves developed near the piezometric surface, in the conditions of long-lasting stabilized flow and they are related to previous levels of erosion. This type of horizontal cave systems is well known in another karst areas of the world also in the Alpine karst (Audra, 1994, 1995, 2001, 2004; Maire, 1990, Bini, 2001). Previous simplified interpretations leaded to identification of various number of cave levels in the Tatra Mts by different authors, from 3 by Rudnicki (1958, 1967) to even 8–12 by Wójcik (1960, 1966, 1968). Recent studies carried out in Czarna Cave (Western Tatra Mountains – Gradziński, Kicińska, 2002) show that the conceptions mentioned aren't universal, and the phreatic loops which were interpreted as a two separate cave levels of different altitudes make the same genetic level. This kind of looping caves were probably developed in epiphreatic conditions during high water due to higher aggressivity of water (Audra, 1994, 2001; Häuselmann, et al., 2001). However if the horizontal sections of passages are the parts of previous transit flow or make emerging river zones, they should have an equivalent in the surface topography outside the cave as planation surfaces or previous alluvial terraces (Palmer, 1987). The problem of the planation surfaces in the Western Tatra Mountains was studied by L. Sawicki (1909), M. Baumgart-Kotarba (1983), M. Klimaszewski (1988). The different interpretations by these authors are presented in the table (Table 1). These authors identified some levels of previous valley bottoms, which should be connected with the cave levels. The Magurska Cave (entrance at 1465 m a.s.l.) developed in Kopa Magury massif is located near the Hala Gąsienicowa which is on the level of the younger submontane planation surface (Fig. 1, Fig. 2).

Table 1

Planation surfaces according to L. Sawicki (1909), M. Baumgart-Kotarba (1983) and M. Klimaszewski (1988)

Planation surface	The altitude [m a.s.l.]	Example of the area
Sawicki (1909)		
I. Montane	about 2000	The tops of the highest peaks
II. Submontane	the Gubałówka level about 11 000	Gubałówka
Baumgart-Kotarba (1983)		
I.	2100	The tops of the highest peaks
II.	1800	
III.	1600	Mała Kopa Królowa
IV.	1400	
V.	1300	
VI.	1100	
Klimaszewski (1988, 1991)		
I. Top	2000–2200	The tops of the highest peaks
II. Montane	1800–1900	
III. Intramontane	1500–1700	Kopa Magury
IV. Submontane	1200–1500	The level of Hala Gąsienicowa (1530–1520)
V. Valley	1100–1400	Lower of the Hala Gąsienicowa (1470–1520)

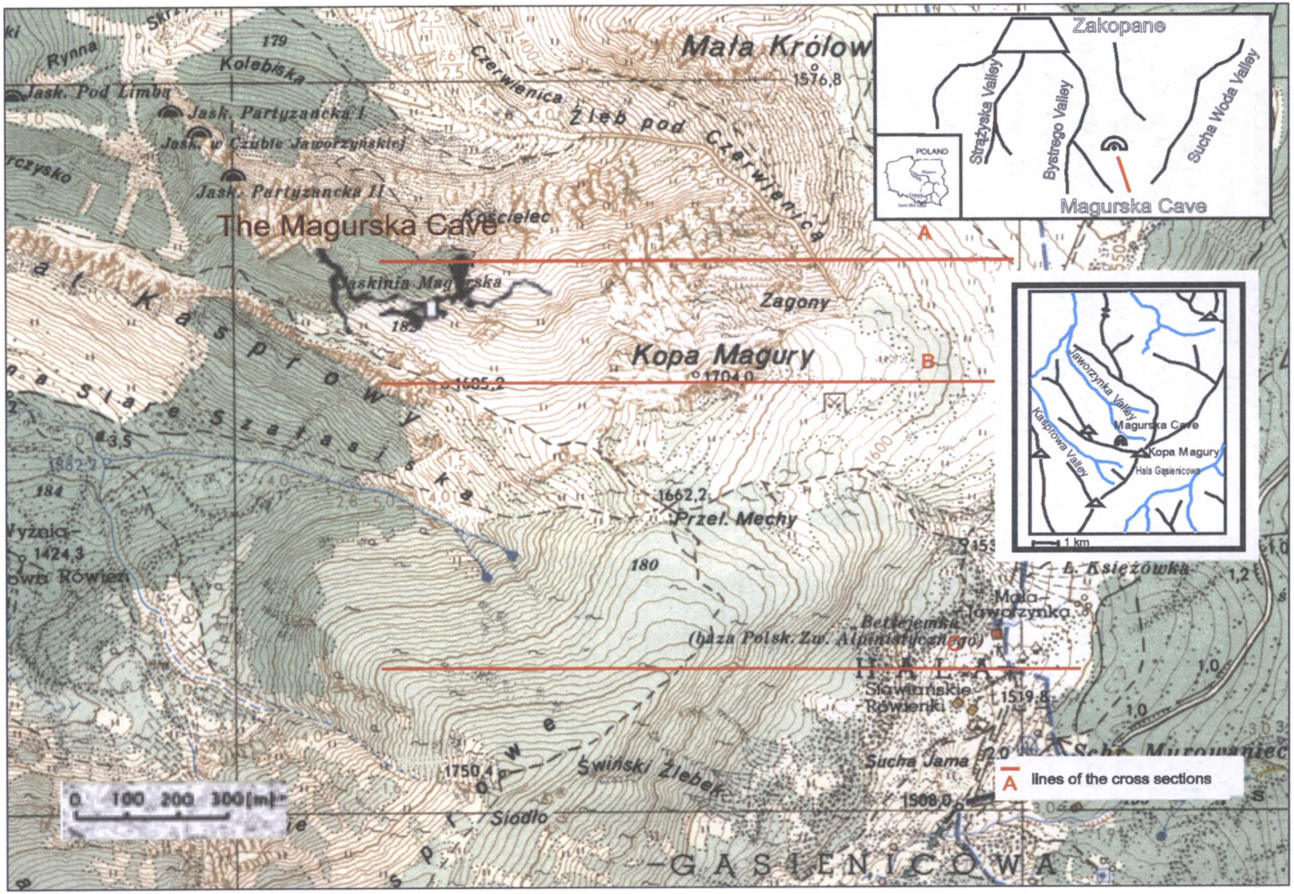


Fig. 1. Location of the Magurska Cave

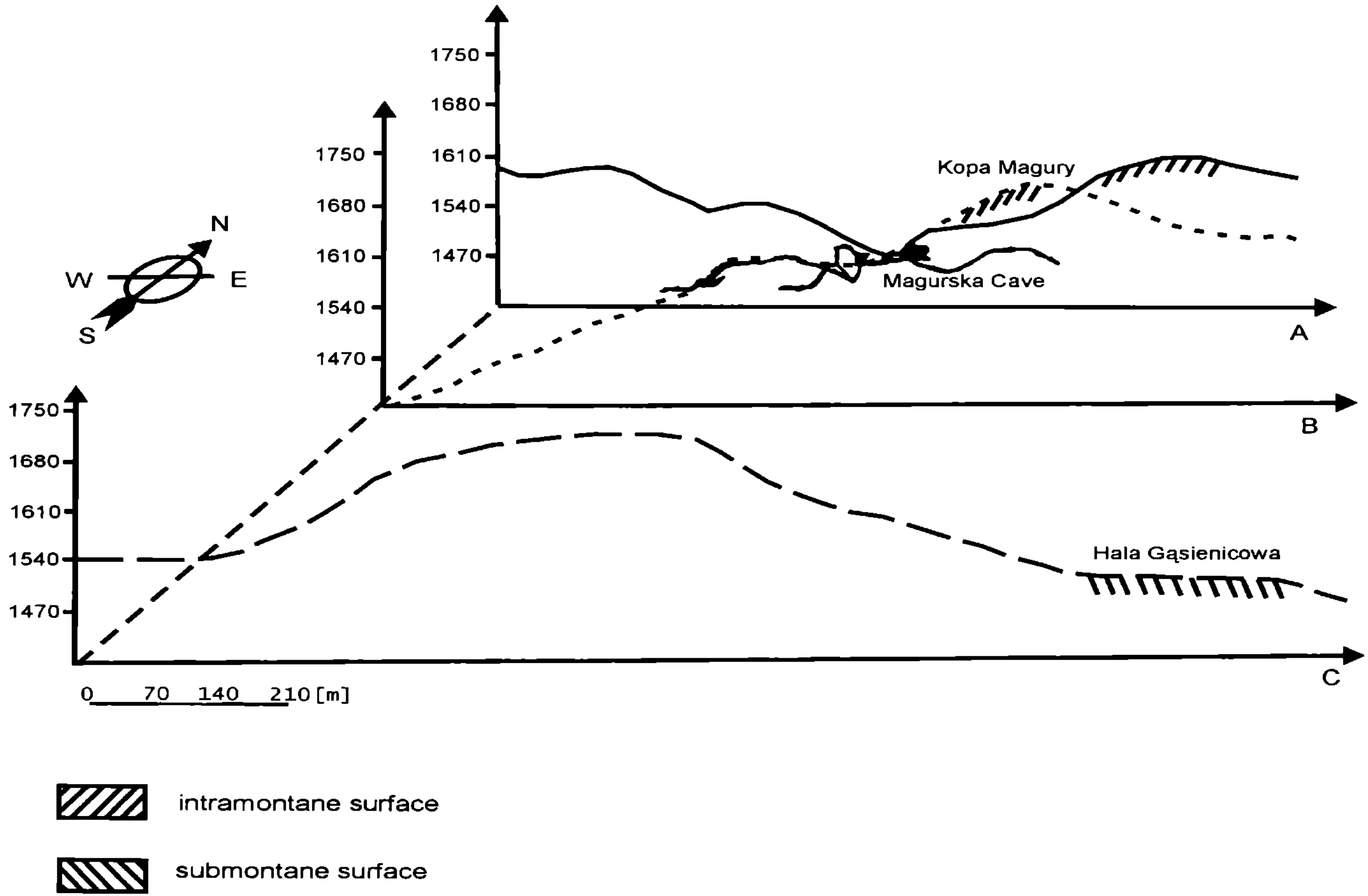


Fig. 2. Location of the Magurska Cave and Hala Gąsienicowa planation surface on the cross section

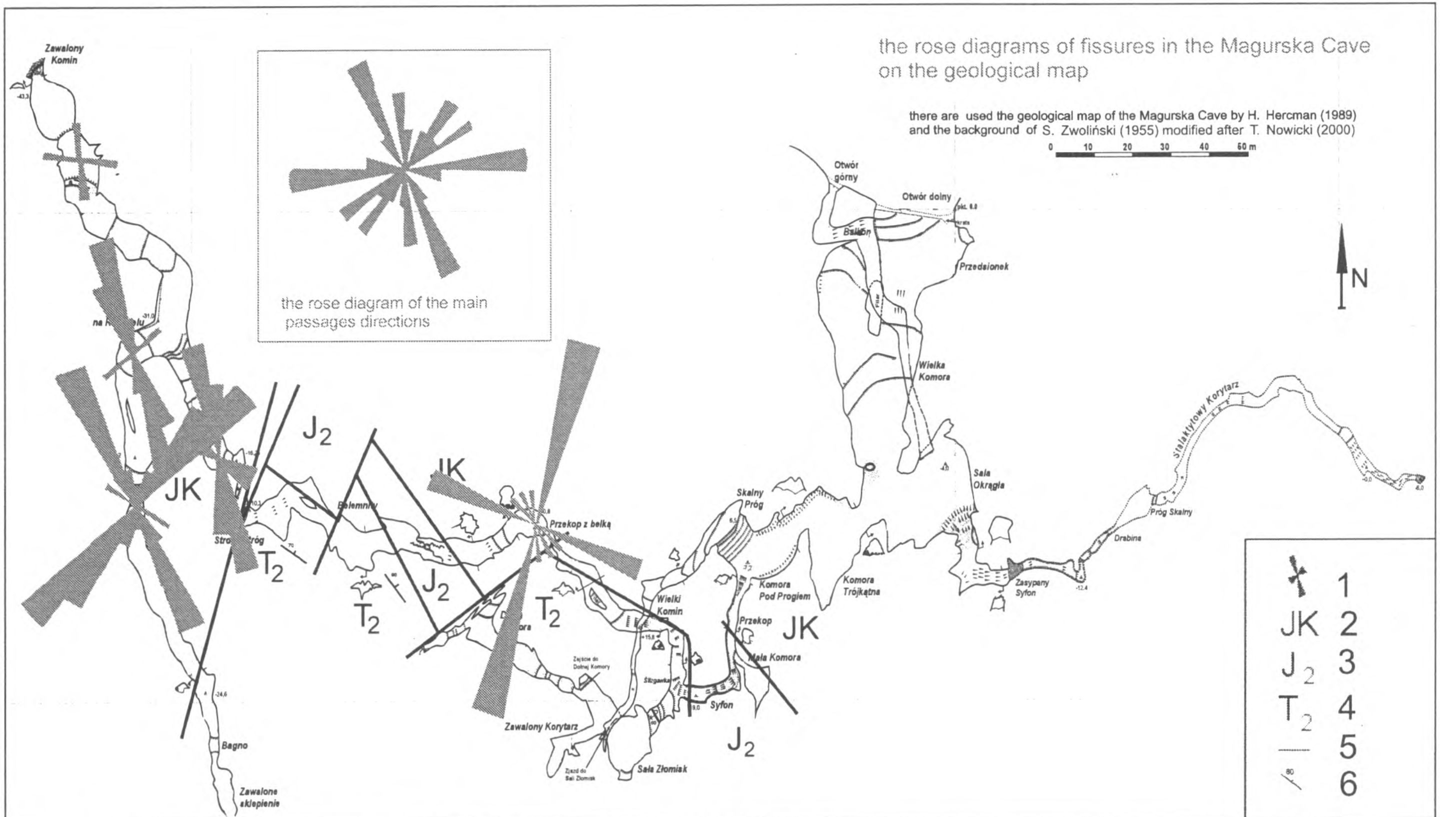


Fig. 3. The rose diagrams of the fissures on the geological map of the Magurska Cave

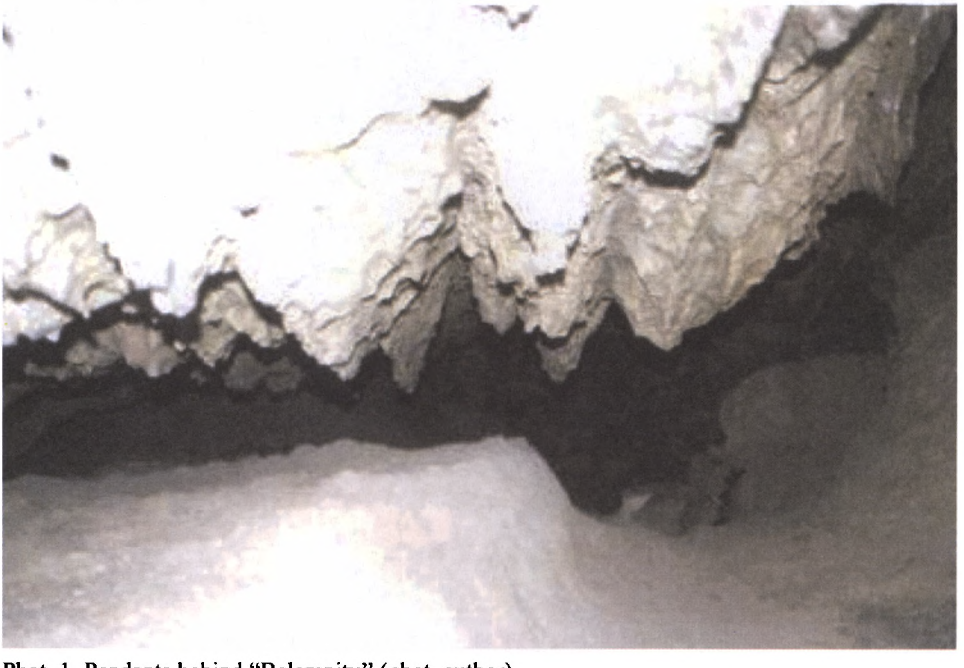
1 – rese diagram of fissures, **2** – Upper Jurassic – lower cretaceous, **3** – Middle Jurassic limestones, **4** – Middle Triassic limestones and dolomiots, **5** -- the main faults, **6** – dip and strike

The direction of the Magurska Cave indicates the possibilities of drainage of the Hala Gąsienicowa through that cave what S. Zwoliński (1987) already suggested. The majority of the conduits course along ESE-WNW strike direction from Hala Gąsienicowa to the Pod Czerwienicą Gully. This cave extends on the similar level with Hala Gąsienicowa. The difference in the altitude doesn't exceed 60 m.

Geological and geomorphological characteristic

The Magurska Cave developed in upper Jurassic – lower Cretaceous limestones, Middle Jurassic limestones and Middle Triassic dolomites and limestones (Hercman, 1989, Fig. 3).

Tectonic fissures measurements were carried out in order to define the significance of tectonic processes in the development of the Magurska Cave. The fissures in thick bedded upper Jurassic – lower Cretaceous limestones are consistent with the direction of passages. In the middle Triassic limestone and dolomite the fissures occur much frequently but are not so prominent. However in these rocks corridors are parallel to the strike of strata.

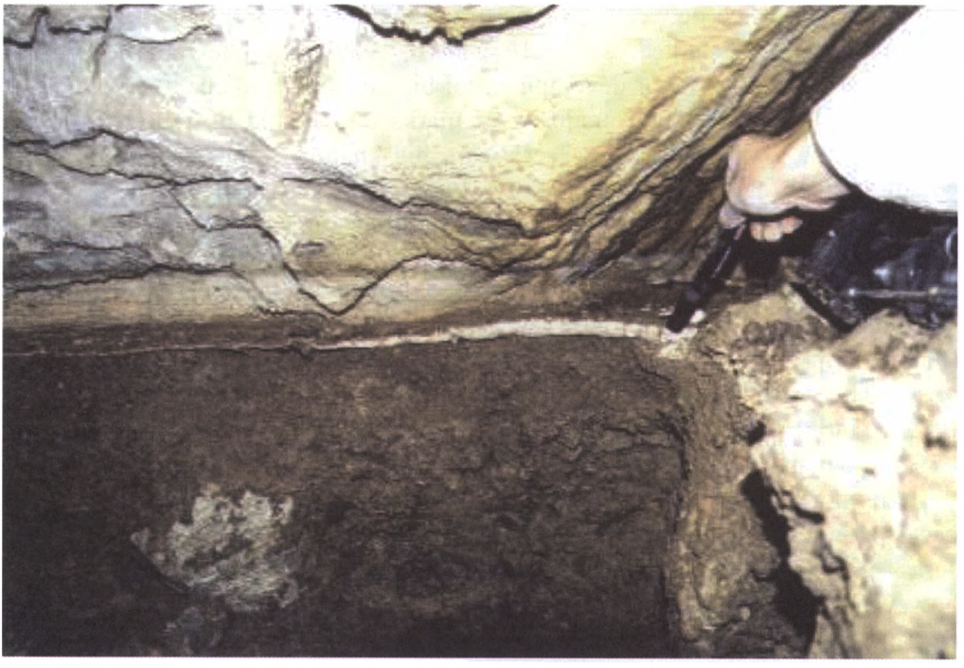


Phot. 1. Pendants behind "Belemnity" (phot. author)

Phot. 2. Scallops on the contact of Middle Jurassic and Middle Triassic rocks (phot. author)

Phot. 3. Composed ceiling pockets in levels in Sala na Rozdzielu (phot. author)

Phot. 4. Calcite curtains after Ślizgawka (phot. author)



Phot. 5. The flowstone cover in Przekop (phot. author)

Phot. 6. The ice stalagmites in Wielka Komora on 18 April 2001 (phot. author)

The dependence between the type of rocks and the corridor morphology is well noticed in the studied cave (Hercman, 1989). The late Jurassic – early Cretaceous limestone favor development of big channels and chambers. They're cut by the fissures, and the majority of marks of phreatic flow are destroyed by collapsing. Typical for these series are big chambers in the entrance with collapsed walls and roofs (points 2, 3, 4, Fig. 4, 5).

The passages in the middle Jurassic limestones are narrow. The walls and the roofs in these rocks are covered by numerous forms smoothed by phreatic water. That contrasts with sharp forms developed in middle Triassic dolomites and limestone. This can be observed between Ślizgawka and Przekop z Belką (point 7, Fig. 4) where the corridor is developed on the contact of these two series. The north side of that section abounds in oval phreatic forms, while the left side build of dark Triassic limestones cut by dense net of calcite veins is full of small pendants (Phot. 1, Phot. 2).

The morphology typical both for the vadose zone and for the phreatic zone occurs along the whole cave. In the entrance part of the cave developed in the upper Jurassic – lower Cretaceous limestones, the marks of phreatic flow are very rare, however there are typical phreatic forms developed on the fissures in the chambers near the entrance. The similar situation concerns the other parts of the cave made in the same series – behind Przekop z Belką (point 8, Fig. 4) and behind Stromy Próg (point 12, Fig. 4). Here the collapsed material is more abundant, however there are

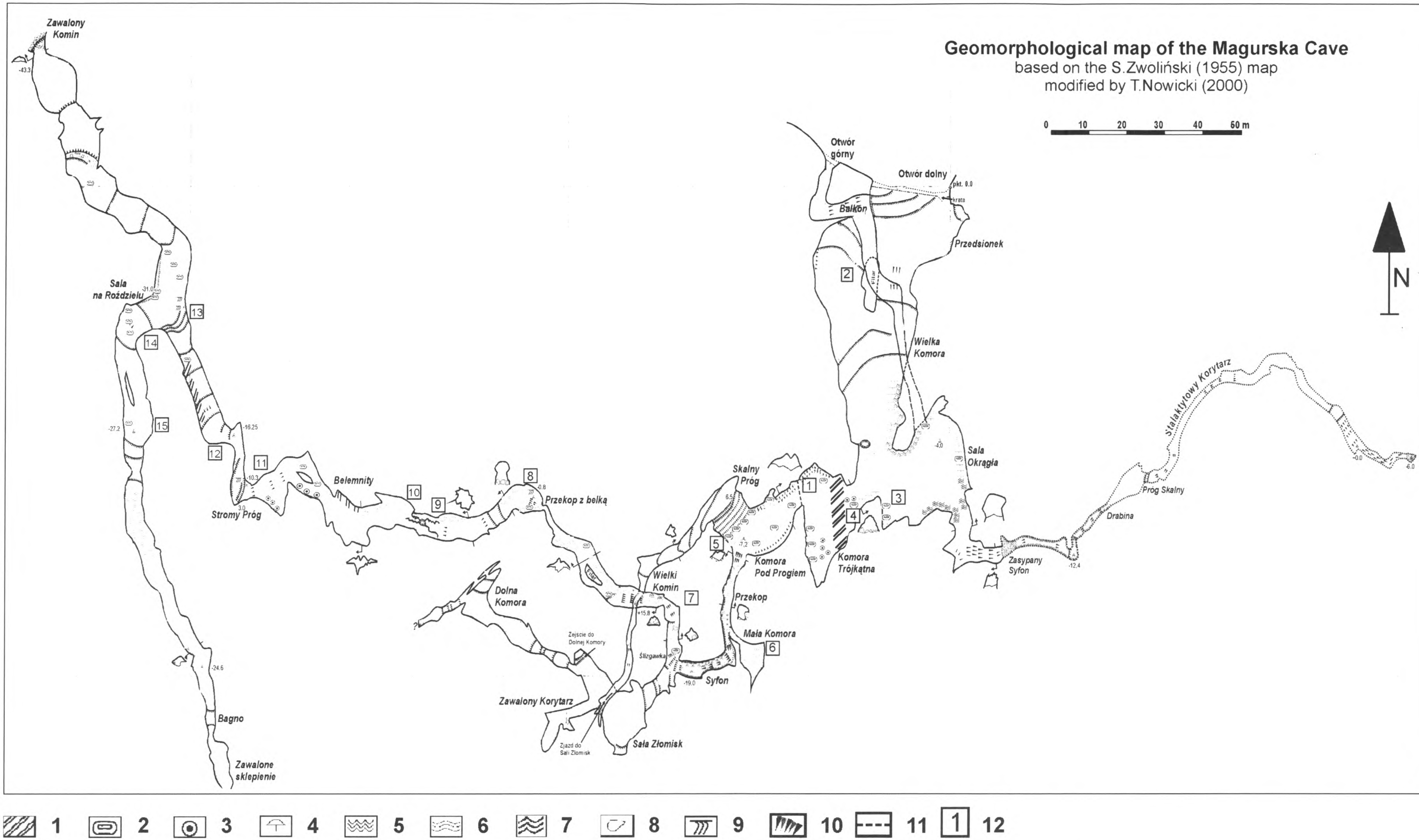


Fig. 4. Geomorphological map of the Magurska Cave

1 – plain roofs, 2 – ceiling pockets, 3 – pendants, 4 – fungoidal concretions, 5 – woolly flowstone formed of moonmilk, 6 – speleothems, 7 – moonmilk flowstone, 8 – scallops; 9 – longitudinal channels, 10 – steep floor and tresholds, 11 – the range of frost phenomena, 12 – points related to the text

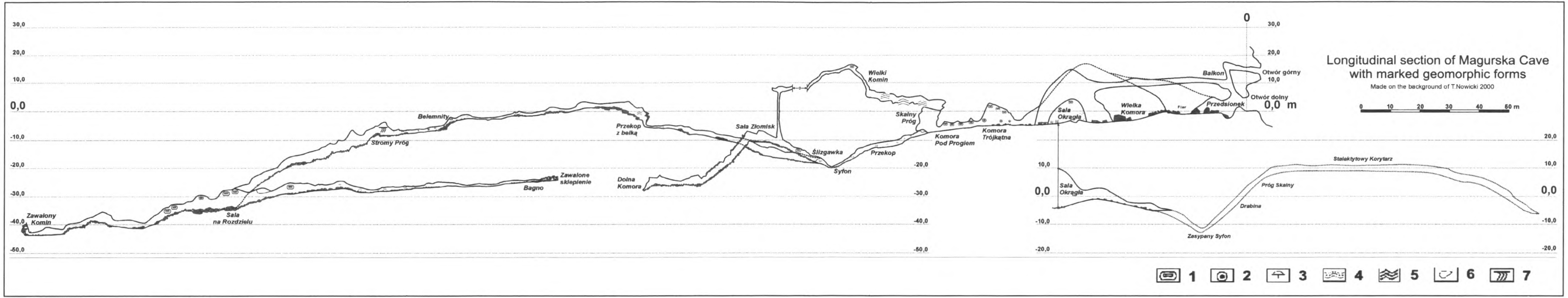


Fig. 5. Longitudinal section of the Magurska Cave in the Western Tatra Mts with geomorphological features

1 – ceilling pockets, 2 – pendants, 3 – fungoidal concretions, 4 – speleothems, 5 – moonmilk flowstones, 7 – longitudial channels

also many solution pockets or chimneys in the roofs. The Sala na Rozdzielu (Phot. 3, points 13, 14, Fig. 4) is a chamber where solution pockets make systems along the fissures. They are often double or repeatedly put one into an other.

The older forms developed in phreatic conditions were overlapped by vadose features of the late Neogene and the beginning of Pleistocene. With the massif uplift and the valleys deepening, the Magurska Cave was dried. In these vadose conditions the collapsing processes became more intense and the speleothems were deposited (Phot. 4). Next climatic changes related to the glacial and interglacial periods caused the return of water flows several times, which is seen in the cave by the fluvial sediments and speleothems. There are flowstones in the Przekop covering the sediments what is the evidence that drying of this cave occurred two times in the late Pleistocene and Holocene (Hercman et al. 1987; Hercman, 1991) (Phot. 5, point 5 Fig. 4).

The changing climatic conditions have their records inside the cave. However, it's difficult to define the number of phreatic and vadose condition successions, because the older forms are smoothed over by the younger forms.

Influence of Magurska Cave's present microclimate on its contemporary shaping

The processes of cave evolution is still active, therefore it was necessary to identify the sub-zero temperature influencing the cave morphology. The temperature measurements and the climatic observations were carried out from November 2000 to June 2002. The main distinguished zone with the unquestionable importance in cave development is the dynamic zone and particularly its part limited by the range of the isotherm 0°C – adjacent to the entrance zone (Pulina, 1960). It comprises the huge chambers near the entrance and reaches the Komora pod Progiem. The ice stalagmites and flowstones exist here till July and reappear in autumn (September –October). They reached the greatest dimentions in April 2001 (Phot. 6, point 1, Fig. 4). The entrance of the cave was almost completely blocked by the snow. In July 2001 the ice sinters were still present, but much smaller. In September the melting ice got to Komora Trójkątna and in November there were only few of them. The range of frost processes includes the great chambers near the entrance, which morphology clearly shows intensive frost weathering. The walls and the roofs are broken down and covered from the east side by moonmilk and fungoidal concretions. They are particularly abundant in Okrągła Komora (point 3, Fig. 4), where they cover the walls with a very thick layer. This type of speleothems genesis is often related to the occurrence of microorganisms in the cave (Gradziński, Radomski, 1957), and the activity of cryochemical processes (Pulinowa, Pulina, 1972). That is why these speleothems should appear near the entrance only. It is proved in the Magurska Cave, where their presence is restricted to the great chambers near the entrance, however they also occur in Mała Komora (point 6, Fig. 4) and behind Ślizgawka. Exceptionally the fungoidal concretions were noticed also on the eastern wall of the south passage behind Sala na Rozdzielu (point 15, Fig. 4). It may be explained by the previous contact with the surface area.

Remarks on the Magurska Cave genesis

The origin of the Magurska Cave may be dated back to the period of the extensive development of planation surfaces. Kopa Magury massif is related to the Intramontane planation surface (Klimaszewski, 1988), located on the altitude of 1500–1700 m a.s.l. (Table 1). Hala Gąsienicowa planation surface must be younger, therefore it refers to the Submontane planation surface (1200–1500 m a.s.l). Its genesis is linked to lower Pliocene (Klimaszewski, 1988) according to the results of geological-geomorphologic correlation studies. This period is regarded as convenient to large cave systems developing due to subtropical climatic conditions, in southern Alps too (Bini, 2002).

The planation surfaces were formed in the periods of tectonic stabilization. The weathered material was eroded and washed from the ridges into the caves in the karstic areas. The Magurska Cave could be one of such caves what is confirmed by:

- great dimentions of the chambers near the entrance of the cave;
- the S-N direction of the chambers adjacent to the entrance, from Hala Gąsienicowa to Pod Czerwieniec gully, which is different from probably younger parts of that cave going to the NW (Hercman, 1991);
- small denivelation between the dolines in Hala Gąsienicowa and the Magurska Cave corridors;
- presence of quartz sand and granite pebbles in the cave (Wójcik, 1960, 1966, Rudnicki, 1967).

In the early Miocene the oblique uplifting of the Tatra Mountains accelerated consequent development of valleys. The Kopa Magury massif is developed in limestones of the Giewont partial nappe, isolated from the lower sub-Tatric Nappe by the impermeable rocks. That bed prevents the flow to the north (Zwoliński, 1955). That's why water drainage directed from Hala Gąsienicowa to NW. However the great entrance chambers do not follow this model and they direct towards the N. Probably, these parts of the cave are connected with the old erosion base in the north and they developed in the period of tectonic stagnation close to perennial watertable. The outflow could be on the contact with the impermeable rocks of the sub-Tatric nappe as a big resurgence.

Hala Gąsienicowa represents a surface where different karst forms, specially dolines develop. They could be related to the system of swallows existing before the Pleistocene, inputting waters into the Magurska Cave. The material derived from crystalline rocks fond in the cave, which come from the crystaline Goryczkowa tectonic cap (Hercman 1986, 1991, Hercman et al., 1987) located on the SW don't exclude the Magurska Cave from Hala Gąsienicowa drainage system. The sediments characteristic for metamorphic rocks can be the evidence of greater range of "Crystalline Goryczkowa Island" in Neogene as H. Hercman mentioned (1986). It is possible that these rocks occurred also on Hala Gąsienicowa area. Another probability is the transport of weathered metamorphic rock from south by the rivers carrying material into the cave.

The Magurska Cave consists of two independent systems (Hercman, 1991). The older one directed water to N through the Great Chambers, and the younger one which directed water first to NE to Jaworzynka Valley, and next to NW to Kasprowa Valley as the deposits analyses by D. Kicińska (1996) show. Probably these passages developed in epiphreatic zone, as vivid loops can be here observed (Fig. 5).

In the cave evolution the canal enlarging effect made by water under pressure depended on the kind of the weathered rocks. Therefore the corridors developed in different series differ in their dimensions. The water flowed to the present entrance were slowed down by more resistant for the karstification middle Jurassic series what caused intensive enlarging of corridors developed in the upper Jurassic rocks (point 8, Fig. 3). The sort of rock influenced also later processes in the vadose conditions. The tectonic uplift and the cave drying up in the late Pliocene caused the activation of collapsing and creating of speleothems.

The largest collapses took place in the middle Triassic rocks and also in the upper Jurassic – lower Cretaceous series, cut by very thick fissures. The passages in the middle Jurassic rocks are the least modified by these processes.

The changeability of the conditions in the cave was the effect of varying climate conditions of the end of Neogene and the beginning of Pleistocene. Each kataglacial phase accelerated the flow of melting water with a reach load of fluvioglacial sediments (Wójcik, 1966). With the drying up of the cave during the interglacials, there came the convenient conditions for collapse processes and the speleothems depositions. As the results of datatings of deposits made by H. Hercman (1991) (Hercman et al., 1987) the great collapse which joined two previously independent parts of the cave took place before the Riss-Würm interglacial.

The present morphogenic processes mainly depend on the air temperature. The range of the isotherm 0°C determines the present frost weathering and the intermited ice development, and the range of the zone with the day temperature fluctuation is the condition of moonmilk and fungoidal concretions development.

Conclusion

The origin of Magurska Cave may be dated by the Neogene. It is the result of long subterranean water circulation in the widest tectonical fissures. Its system was made by joining two independent parts (Hercman, 1991). The older of them directed the water from Hala Gąsienicowa Planation Surface to N to Jaworzynka Valley, where the outflow took place at the contact with the impermeable rock as a big resurgence. It evolved probably close to the perennial watertable in the conditions of long lasting stabilized flow. The second system, created during high water in epiphreatic conditions directed water to the Jaworzynka Valley and then to NW direction to Kasprowa Valley (Kicińska, 1996). These two parts were joined by the great collapse before Eemian interglacial according to Hercman (1991). The last glaciation (22–10 ka) influenced the deposition of limestone pebbles occurred till the first siphon and their mixing with deposited earlier bones and silts in the big chambers (Hercman, 1991; Hercman et al., 1987).

The conditions in the cave changed many times with the changeable climate of the Neogene and the beginning of Pleistocene. In the periods of the under pressure very aggressive high water flow the effect of corridors enlarging was determined by the sort of the rocks. The slowed down flow on the contact with the least karstyfying series (middle Jurassic limestones) enhanced the intensive development of more susceptible for dissolution rocks (Upper Jurassic limestone) (point **8**, Fig. 4).

The sort of the rocks is also significant in the vadose conditions, as the greatest collapsing is found in the middle Triassic and upper Jurassic – lower Cretaceous rocks.

The actual morphogenic processes are mainly influenced by the sub-zero air temperature. The range of 0°C isotherm decides on present frost weathering limited to the big chambers adjacent to the entrance. The range of daily temperature fluctuations is also crucial for morphological processes, as is the factor determining the moon milk and the fungoidal concretions development.

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Patrycja Pawłowska-Bielawska

Morfologia Jaskini Magurskiej i jej geneza jako systemu drenującego powierzchnię zrównania Hali Gąsienicowej

Streszczenie

Podczas analizy przekrojów podłużnych przez systemy wielu jaskiń Tatr Zachodnich narzuca się wyraźna systematyczność pojawiania się poziomych odcinków korytarzy poprzecinanych głębokimi studniami. Zgodnie ze znanymi poglądami na genezę jaskiń Tatr Zachodnich (Wójcik, 1960; 1966; 1968; Rudnicki, 1967; Grodzicki, 1991), poziome odcinki tworzyły się w pobliżu zwierciadła wód w neogeńskich warunkach długotrwałego, ustabilizowanego przepływu i nawiązują do dawnych poziomów bazy erozyjnej. Tego typu stare horyzontalne systemy jaskiniowe są opisane także w wielu innych obszarach, m.in. w krasie alpejskim (Audra, 1994; 1995; 2001; 2004; Maire, 1990, Bini, 2001). Ostatnie badania prowadzone w Jaskini Czarnej w Tatrach Zachodnich (Gradziński, Kicińska, 2002) wykazały, że przytoczone koncepcje nie zawsze

są słuszne, a poziomy korytarzy rozwinięte na różnych wysokościach nie muszą nawiązywać do minionych poziomów bazy erozyjnej, lecz mogą stanowić to samo genetycznie piętro. Jeżeli jednak poziome odcinki korytarzy stanowią fragmenty dawnych jaskiń przepływowych bądź są strefami wywierzyskowymi, to powinny mieć swoje odpowiedniki w morfologii terenu, poza jaskinią w postaci powierzchni zrównań albo dawnych den dolinnych.

Zagadnienie powierzchni zrównań w Tatrach było przedmiotem badań m.in. L. Sawickiego (1909), M. Baumgart-Kotarby (1983) i M. Klimaszewskiego (1988). Zidentyfikowali oni kilka poziomów dawnych den dolinnych, które nawiązują do poziomów jaskiniowych (tab.1). Jaskinia Magurska rozwinięta w masywie Kopy Magury na wysokości 1465 m n.p.m. znajduje się w sąsiedztwie Hali Gąsienicowej, położonej na poziomie pogórskiej powierzchni zrównania (ryc. 1).

Kierunki korytarzy Jaskini Magurskiej wskazują na możliwość drenażu Hali Gąsienicowej przez tę jaskinię. Przebieg większej części korytarzy jest zgodny z kierunkiem SE-NW. Natomiast największe sale przy otworze nawiązują do kierunku S-N, biegnącego od Doliny Gąsienicowej w stronę Żlebu pod Czerwienicą i kontaktu z nieprzepuszczalnymi skałami płaszczowiny reglowej. Poziom, na którym rozwinięta jest badana jaskinia, nie odbiega znacznie od poziomu Hali Gąsienicowej. Różnica wysokości względnych NE końca korytarza Jaskini Magurskiej i Hali Gąsienicowej wynosi ok. 60 m. Również znajdujące się w jaskini osady klastyczne, pochodzące prawdopodobnie z obszaru krystalicznej Wyspy Goryczkowej (Hercman, 1986), nie wykluczają możliwości drenażu Doliny Stawów Gąsienicowych przez system Jaskini Magurskiej, jako że w momencie tworzenia się systemu zasięg "wyspy Goryczkowej" mógł być większy, lub że osad został przetransportowany przez potoki. Stamtąd cieki powierzchniowe, ginące w ponorach, mogły wprowadzić ten materiał do jaskini. Ponadto w osadach z sal wstępnych nie stwierdzono minerałów charakterystycznych dla skał metamorficznych (Hercman, 1991).

Początek kształtowania się Jaskini Magurskiej sięga prawdopodobnie końca neogenu (Hercman, 1991). Stabilizacja tektoniczna i korzystne warunki termiczne tego okresu sprzyjały rozwojowi dużych poziomych korytarzy, jak we wstępnej części jaskini, rozwijającej się w pobliżu zwierciadła wód podziemnych. Prowadziła ona wody na północ, gdzie na kontakcie z nieprzepuszczalnymi skałami płaszczowiny reglowej następował wypływ w postaci wywierzyska. Studia morfologiczne prowadzone w południowo-zachodniej, prawdopodobnie młodszej części jaskini wskazują na tworzenie się tego systemu w strefie epifreatycznej w warunkach wysokiego zwierciadła wód podziemnych.

Obserwacje morfologiczne przeprowadzone w jaskini wskazują na wyraźne wahania zwierciadła wód podziemnych, odpowiadające zmieniającym się warunkom klimatycznym końca neogenu i plejstocenu. W okresach przepływu pod ciśnieniem agresywnych wód wysokich stanów efekt poszerzania korytarzy był determinowany rodzajem skał, w których zachodziła korozja. Dlatego kontaktujące się ze sobą korytarze wykształcone w różnych seriach znacznie różnią się wielkością. Wody wpływające z utworów "malmoneokomu" do utworów jury środkowej były hamowane przez słabiej krasowiejący, wąski odcinek dalszy i konwekcyjnie poszerzały korytarz utworzony w wapieniach górnej jury (np. okolice Przekopu z Belką). Rodzaj skał wpłynął także na późniejsze zjawiska zachodzące w odmiennych warunkach wadycznych. Najwięcej zawalisk stwierdzono w skałach środkowego triasu i "malmoneokomu". Każdemu interglacjałowi towarzyszył prawdopodobnie przepływ wód roztopowych wraz z bogatym ładunkiem osadów fluwialnych. Po ustąpieniu wód następowały momenty dogodne do tworzenia się pokryw naciekowych i odpadania grawitacyjnego fragmentów skał.

Na zachodzące współcześnie procesy rzeźbotwórcze duży wpływ ma temperatura powietrza. Zasięg izotermy 0°C decyduje o współcześnie zachodzącym wietrzeniu mrozowym i tworzeniu się nacieków lodowych, a zasięg strefy przejściowej z notowanymi wahaniami temperatury w cyklu dobowym ma wpływ na tworzenie się nacieków typu mleka wapiennego i grzybków. W Jaskini

Magurskiej procesy mrozowe sięgają Komory pod Progiem i wyraźnie modelują rzeźbę stropów i ścian w rezultacie wietrzenia mrozowego, ale wpływają też na przekształcenie namuliska w dnie jaskini w wyniku procesów segregacji mrozowej.

Patrycja Pawłowska-Bielawska

La morphologie de Jaskinia Magurska et sa genèse comme un système drainant la surface d'aplanissement de l'Alpage de Gąsienicowa

Résumé

Au cours d'une analyse des coupes longitudinales de systèmes de plusieurs grottes dans les Tatras de l'ouest, nous avons repéré une récurrence nette dans l'apparition des fragments horizontaux des couloirs, entrecoupés de puits profonds. Conformément aux opinions connues sur la genèse des cavernes dans les Tatras de l'ouest (Wójcik, 1960; 1966; 1968; Rudnicki, 1967; Grodzicki, 1991), des fragments horizontaux se formaient dans le voisinage de la surface d'eau, dans les conditions neogénès du passage stable et de longue durée; ils évoquent des anciens niveau de la base d'érosion. Des vieux systèmes horizontaux de cavernes de ce type sont-ils aussi décrits dans d'autres terrains assez nombreux, entre autres dans le karst alpin (Audra, 1994; 1995; 2001; 2004; Maire, 1990; Bini, 2001). Les dernières recherches, menées dans Jaskinia Czarna (les Tatras de l'ouest) – Gradziński, Kicińska 2002, ont démontré que les conceptions citées ne sont pas toujours correctes et que les niveaux des couloirs tracés à différents niveaux ne doivent pas être liés aux niveaux anciens de la base d'érosion mais ils peuvent constituer la même couche génétique. Pourtant si les sections horizontales des couloirs constituent des fragments des grottes de passage ou sont des zones de sources vauclusiennes, elles devraient avoir ses correspondants dans la morphologie du terrain; hors de la caverne en forme d'une surface d'aplanissement ou des fonds de vallée anciens.

La question des surfaces d'aplanissement dans les Tatras a été l'objet de recherches entre autres de L. Sawicki (1909), M. Baumgart-Kotarba (1983) et M. Klimaszewski (1988). Ils ont identifié quelques niveaux des fonds de vallée anciens qui sont liés aux niveaux des cavernes (tab.1). Jaskinia Magurska située dans le massif de Kopa Magury à l'altitude de 1465 m, se trouve dans le voisinage de l'Alpage de Gąsienicowa, placé au niveau de la surface d'aplanissement (Fig. 1).

La direction des couloirs de Jaskinia Magurska prouve la possibilité du drainage de l'Alpage de Gąsienicowa par cette caverne. La localisation de la grande partie de couloirs est conforme à la direction SE-NW, cependant les grottes les plus grandes à la proximité à l'orifice sont orientées S-N, selon la ravine de Czerwienica et le contact avec des roches impénétrables du domaine compressif. Le niveau sur lequel est placée la grotte en question ne différencie pas beaucoup du niveau de l'Alpage de Gąsienicowa. La différence des altitudes relatives NE de la fin du couloir de Jaskinia Magurska et de l'Alpage de Gąsienicowa est égal à environ 60 m. Aussi les sédiments clastiques démontrés dans la caverne, provenant probablement du terrain cristallisé de Wyspa Goryczkowa (Hercman, 1986), n'excluent-ils pas la possibilité du drainage de la vallée de Stawy Gąsienicowe par le système de Jaskinia Magurska puisque au moment de la formation du système la portée de Wyspa Goryczkowa pouvait être plus grande, ou bien les sédiments pouvaient être transportés par des torrents. De là des cours d'eau, se perdant dans des gouffres absorbant, pouvaient faire entrer ce matériel dans la caverne. En plus, dans des sédiments des salles de seuil on n'a pas constaté des minéraux typiques pour des roches métamorphiques (Hercman, 1991).

Le début de la formation de Jaskinia Magurska date probablement de la fin de néogène (Hercman, 1991). La stabilisation tectonique et des conditions thermiques favorables de cette

période ont facilité le développement de grands couloirs horizontaux, comme dans la partie de seuil de la caverne, formée dans les alentours de la surface libre d'eau souterraine. Elle menait l'eau vers le nord où, dans le contact avec des roches imperméables du domaine compressif avait lieu un écoulement en forme de la source vauclusienne. Les études morphologiques menées dans la partie sud-ouest, probablement plus jeune, de la caverne démontrent la formation de ce système dans la zone phréatique dans des conditions de la surface libre d'eau souterraine haute.

Les observations morphologiques poursuivies dans la caverne prouvent des variabilités discernables de la surface d'eau correspondant à des conditions climatiques changeant de la fin du néogène et du pléistocène. Dans les périodes du passage de la pression des eaux agressives aux niveaux hauts l'effet de l'élargissement des couloirs a été déterminé par le type des roches, dans lesquels avait lieu la corrosion. C'est pourquoi des couloirs voisins, formés dans des séries différentes, diffèrent nettement de l'ampleur. Les eaux écoulant des formes du « malm – néocomien » aux structures du jurassique moyen étaient freinées par une fraction moins corrosive et étroite, et elles élargissaient par la convection le couloir formé dans les calcaires du jurassique inférieur (p. ex. la région de Przekop et Belka). Le type de roches aussi influençait-il des phénomènes postérieurs, observés dans de différentes conditions vadoses. Nous avons constaté le plus grand nombre d'éboulis dans les roches du trias moyen et du « malm-néocomien ». Chaque interglaciaire était probablement accompagné du passage des eaux dégelées avec une charge des sédiments fluviaux. Après la récession des eaux les conditions favorables pour la formation des roches d'infiltration et pour la chute gravitationnelle des fragments de la roche.

La température de l'air influence profondément des processus actuels de la formation du relief. L'étendue de l'isotherme 0°C décide de la désagrégation du gel qui s'effectue actuellement et de la formation des concrétions glaciales, pendant que l'étendue de la zone de passage avec des variations des températures dans le cycle diurne influence la formation des solidifications de l'échaudage et des stalagmites en forme de champignons. Dans Jaskinia Magurska les processus de gel touchent Komora pod Progiem et modèlent visiblement le relief des plafonds et des parois par la désagrégation du gel mais aussi influencent-ils la transformation du fond de la grotte en résultat des processus de la ségrégation de gel.

First received: October 2003.

„Kras i Speleologia". T. 12 (XXI). Katowice 2008
Prace Naukowe Uniwersytetu Śląskiego nr 2537

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Sulphate speleothems in "Pomorzany" Zn-Pb ore mine, Southern Poland

Abstract: Underground mining of Zn-Pb ore deposits stimulates the development of acid mine drainage (AMD) processes. In conditions of high humidity (92–95%) sulphate forms such as stalagmites, stalactites and others are found on side walls of excavations. They can increase in size up to 2 m and their colours are white, greenish or yellow. These forms comprise mainly epsomite and melanterite minerals including other sulphates such as hexahydrite, pentahydrite, chvaleticeite, starkeyite, szomolnokite, rozenite, copiapite, boyleite, bianchite, anglesite and gypsum. A lowering of the humidity level may cause a change in the mineralogical composition of sulphate minerals, e.g., hexahydrite can transform into pentahydrite and quite often into tetra-hydrous starkeyite and rozenite. These minerals are only stable in conditions of high mine air humidity and an increase in mine water inflow results in dissolution and water pollution with sulphate ions and heavy metals. ESEM analyses revealed that sulphate speleothems included numerous sub-microscopic sulphides (up to 200 μm) such as galena, sphalerite, piryte, markasite and carbonate such as smithsonite, cerrusite and also hemimorfite and native sulphur. Sulphate contents in non-exploited Zn-Pb ores range from 0.05 to 4% mass fraction and even up to 8% in oxide ores occurring near the drainage zone (e.g., Klucze ore). The sulphates are characterized by high contents of metals such as Zn (up to 11 594 mg $\cdot$ kg^{-1}), Fe (78 709 mg $\cdot$ kg^{-1}), Cd (24.8 mg $\cdot$ kg^{-1}) and Mn (322.4 mg $\cdot$ kg^{-1}), which is why these metals can be activated during the sulfide oxidation phase.

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Introduction

An effective exploitation of shallow lying ore deposits in considerably watery conditions can accelerate the development of the weathering processes of ore minerals and co-occurring carbonates (Cabała, 2001; Jambor et al., 2000). Oxidation is a complex process that proceeds rapidly when sulphides are exposed to air flow and humidity. The crystallization sequence of sulphates depends on environmental conditions such as ambient humidity and temperature and also the following thermodynamic factors: enthalpy, entropy and Gibbs energy (Jambor et al., 2000). The oxidation of Zn-Pb-Fe sulfides and dissolution of carbonates results in the enrichment of the aeration zone with ions such as Fe^{2+}, Zn^{2+}, Mg^{2+}, Ca^{2+} and SO_4^{2}. Conditions of crystallisation of hydrated sulphate minerals in pyrite deposits were fully described by T. Buckby et al. (2003). The development of sulfide oxidation can cause acid mine drainage (AMD) on a large scale and this has a huge impact on the natural environment in areas of exploitation or tailing ponds of metal sulfide minerals (Alpers et al., 1994; Sracek et al., 2004; Cabała et al., 2004a; Cabała, 2005). Sulphates and metal ions which are leached from a deposit zone infiltrate into intensively drained mine aquifers during the mine operations. Sulphate concentations in the aquifer from the "Pomorzany" mine reach up to 300 mg/dm^3 (Różkowski et al., 1997).

A considerable amount of sulphates occurs in mine excavations just after cutting through the ore deposits and their drainage. They can develop various forms of dripstones such as stalactites, stalagmites, aggregates, clusters and coatings. The dripstones consisting of Mg sulphates are well-known karst formations and can be described as 'salt hair', 'epsomite flowers' and transparent epsomite dripstones (Hill, Forti, 1997). The occurrence of unstable sulphates including metals such as Zn, Fe, Pb, K, Mg can indicate heavy metals migrations in the area under mining operations. The presence and chemical composition of sulphate dripstones allows the scale of the AMD development in a fissured and karstic rock mass to be indirectly estimated.

Site description

The aim of the study is to examine the present sulphate dripstones occurring in the underground excavations in the "Pomorzany" Zn-Pb mine. The "Pomorzany" ore deposits are situated in the area of the "Pomorzany" graben (Fig.1). The

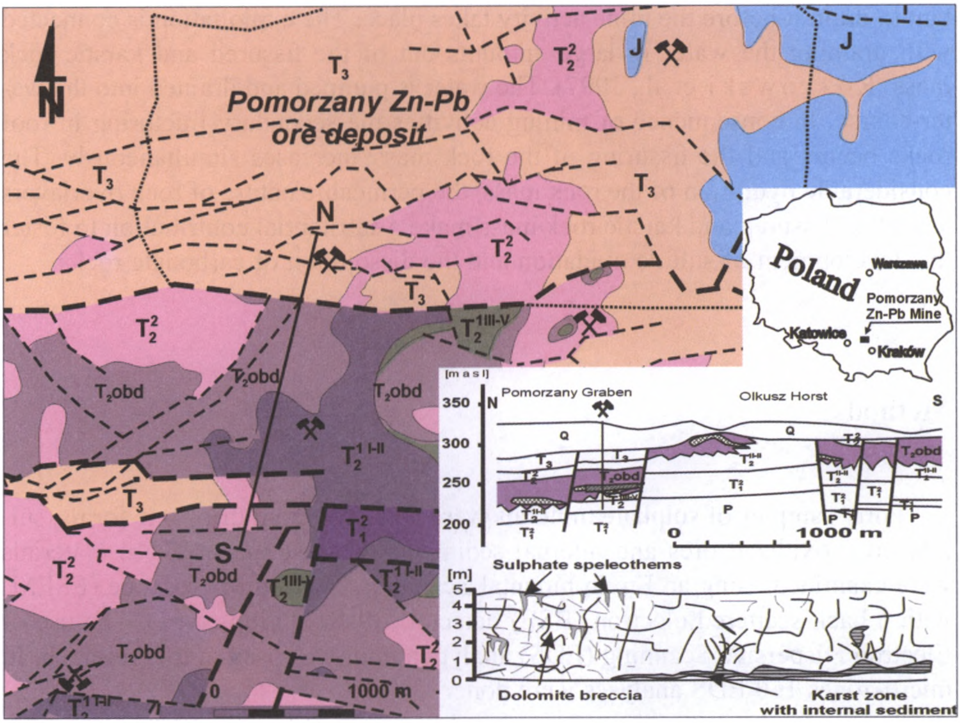


Fig. 1. Location of the "Pomorzany" ore deposit and its cross-section, the sketch of a heading with sulphate speleothems

Q – Quaternary, J – Jurassic, T_3 – Keuper, $T2^2$ – Diplopora dolomites, T2 obd – Ore-Bearing dolomites, $T2^{1III-V}$ – Górażdże, Terebratula and Karchowice Beds, $T2^{1I-II}$ – Gogolin limestones, $T1^3$– Roet, dolomites, P – Permian

ore deposits are exploited using pit shafts which are located several kilometres west of the town of Olkusz. The mine has been under operation since 1968 and the constant decrease in recoverable reserves results in imposing limitations on the prospects of further exploitation in the next 10–12 years. In the mine two main systems of the exploitation have been applied – a pillar-chamber system and a shortwall one. The distinct advantage of applying these is to obtain a greater mobility of mine faces as well as almost complete exploitation of ore deposits. The exploitation activity is carried out using a hydraulic filling. The pillar-chamber systems are applied to exploit a single layer up to 6 m in thickness, whereas the shortwall systems can be used for a multilayer deposit. Before the 1990s there were other systems in use, for example a chamber system with a falling roof and others such as a "subshelf" system with a falling roof and an "85 Pomorzany" which were peculiar to the "Pomorzany" mine only (C a b a ł a, K o n s t a n t y n o w i c z, 1999).

The excavation are conducted mainly in ore-bearing dolomites, and rarely in limestones and marls. When exploiting a new part of a deposit, it is very important to drain it before the mine activity takes place. The exploitation is connected with draining the water in large amounts out of the fissured and karstic rock mass (Różkowski et al., 1997). The water is pumped and drained into the water-course. In consequence of mining activities the secondary fracturing in roof rocks occurs and the fissuring of the rock mass increases simultaneously. The considerable hydration of the rock mass, the permeable nature of rock overlayers as well as fissured and karstic rock mass make a substantial contribution to foster the development of sulfide oxidation and the dissolution of carbonate rocks.

Methods

Forty samples of sulphate minerals were collected from dripstone forms, sulfide ores, oxidized ores and internal sediments of karst space. These materials were examined using an Environmental Scanning Electron Microscope (ESEM) with a back-scattered electron (BSE) detector (30 XL Philips type). The use of Electron Dispersive Scanning (EDS) analytical unit was used in this research. In micro-zones 160 EDS analyses were done.

The mineral composition of the samples was identified by an X-ray diffractometer (Philips PW 3710) using Co Kα X-ray (at 45 kV of voltage and 30 mA of intensity). The impulse counting time was 1–2 sec and the counter track was 0.02°. The amount of sulphate content in Zn-Pb ores was determined on the basis of 618 chemical analyses (spectroscopic and rentgenographic ones) of the samples taken from Olkusz–Zawiercie area and were done in the Laboratory of Geological Company in Cracow, whereas X-ray and microscopy examinations were carried out at the Faculty of Earth Sciences, University of Silesia in Sosnowiec.

Sulphates in Zn-Pb ores in the Silesian–Cracow area

The deposits which occur in the Silesian–Cracow area belong to the MVT (The Mississippi Valley Type) connected with epigenetic ore dolomites. The ores running relatively shallow (to a depth of 200 m) form pseudo-beds and nests in the Triassic carbonate sediments. The chemical composition contains mainly associations of Zn-Pb-Fe sulfides which occur in weakly compacted and fractured dolomites (Viets et al., 1996; Mayer, Sass-Gustkiewicz, 1998; Cabała, Konstantynowicz, 1999). The group of accompanying minerals are represented by barite, calcite and the complex of secondary sulphates, carbonates, oxides, hydroxides and silicates including zinc, iron and lead (Żabiński, 1960; Cabała, 2001).

The ore deposits contain a wide variety of secondary hydrated sulphates such as epsomite, hexahydrite, melanterite, halotrichite, copiapite, rozenite, gypsum, jarosite (Żabiński, 1958; Żabiński, 1960; Kubisz, Żabiński, 1958).

Unstable hydrated sulphates form in an early stage of sulphate oxidation and an excess of Mg^{2+}, Ca^{2+}, Fe^{3+} and SO_4^{2-} ions in the environment results in transforming them into much more stable carbonates and oxides.

The average content of Ca-Mg-Fe-Zn sulphates in Zn-Pb ores in particular deposit areas ranges from 0.05 to 4% (Fig. 2), whereas a considerable content of sulphates can be observed in ore deposits which are characterized by a high oxidation state and the aquifer. In particular, such ore deposits can be found in karst areas connected with mine water drainage. Then the contribution of unstable sulphates in ores can exceed 8% (Klucze deposit, Fig. 2). The detailed identification of sulphate occurrence in ores seems to be largely important for effective exploitation and further ore dressing because the sulphates have an impact on the flotation of galena PbS, sphalerite ZnS and marcasite FeS_2 (Da Silva, 2004; Komosa, 1994).

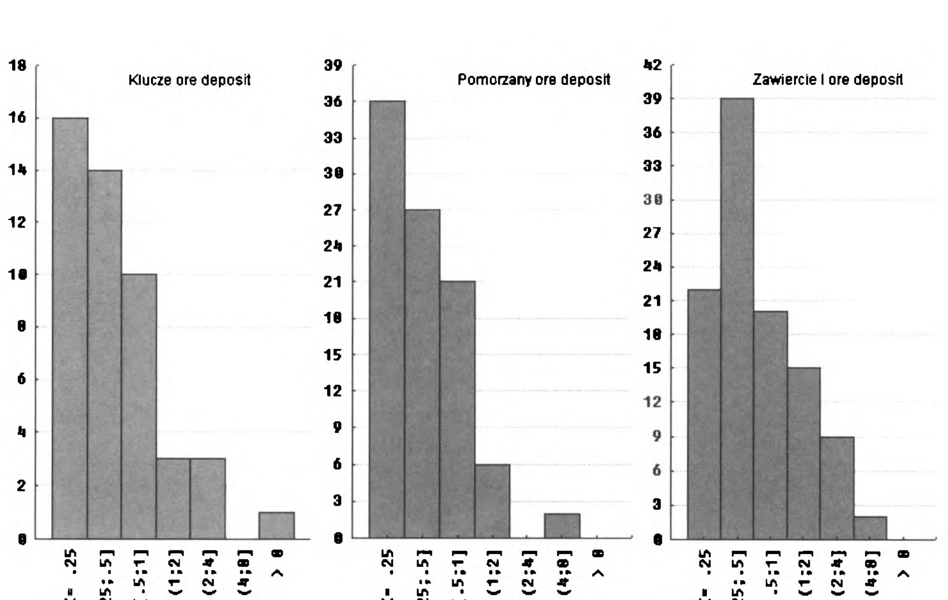


Fig. 2. Bar charts of Ca-Mg-Fe-Zn sulphate content in Zn-Pb ores
Klucze n = 46, Pomorzany n = 91, Zawiercie n = 106 (n – numbers of observation)

Sulphate speleothems in "Pomorzany" Zn-Pb ore deposits

Crystallisation of sulphates occurs in exploited excavations above which macroporous Zn-Pb ores containing colloidal Zn-Fe colloidal sulphides are situated. The formation of the sulphate speleothem structure is conditioned by the acid drainage development connected with infiltrating waters from above lying parts of ore deposits. The speleothem structure can only appear and develop in conditions of high, but stable air humidity.

The use of an X-ray method to determine the chemical composition of dripstones from the "Pomorzany" mine allowed identification of Mg-Fe-Zn-Ca hydrated sulphates and sporadically occurring fine grains of Zn-Pb-Fe sulfides, Zn-Pb carbonates and native sulfur (Table 1). The dripstones comprise mainly Mg-sulphates such as epsomite, hexahydrite and pentahydrite. These minerals can be formed in low pressure and in a range of temperatures from 25°C to 45°C (Chou, Seal II, 2003). Under condition of low humidity epsomite and hexahydrite can release water and transform into pentahydrous pentahydrites. Tetra-hydrous Mg-sulphates such as starkeyite can rarely be found in speleothems. Starkeyite contains the replacement by Fe^{2+} indicating a change in chemical composition with the possibility of turning into rozenite. Such processes are reversible and the increase in humidity can cause transformations into hexahydrite and epsomite. The X-ray analysis of the studied sulphates reveals that Fe^{2+} ions often replace Mg^{2+} and Zn^{2+}, respectively. That is why these sulphates do not occur in pure forms and their accurate identification becomes particularly difficult.

Table 1

Minerals occurring in sulphate speleothems in the "Pomorzany" mine

Mg and Ca sulphates	Epsomite $MgSO_4 \cdot 7H_2O$, Gypsum $CaSO_4 \cdot 2H_2O$, Hexahydrite $MgSO_4 \cdot 6H_2O$, Pentahydrite $MgSO_4 \cdot 5H_2O$, Starkeyite $MgSO_4 \cdot 4H_2O$, Chvaleticeite $(Mn^{2+}Mg)SO_4 \cdot 6H_2O$
Fe sulphates	Melanterite $Fe^{2+}SO_4 \cdot 7H_2O$, Rozenite $FeSO_4 \cdot 4H_2O$, Szomolnokite $Fe^{2+}SO_4\ H_2O$, Siderotil $Fe^{2+}SO_4 \cdot 5H_2O$, Ferrohexahydrite $Fe^{2+}SO_4 \cdot 6H_2O$, Halotrichite $Fe^{2+}Al_2(SO_4)_4 \cdot 22H_2O$, Copiapite $Fe^{2+}Fe^{3+}_4(SO_4)_6(OH)_2 \cdot 20H_2$,
Zn and Pb sulphates	Boyleite $(Zn,Mg)SO_4 \cdot 4H_2O$, Bianchite $(Zn,Fe^{2+})SO_4 \cdot 6H_2O$, Anglesite $PbSO_4$
Others	Galena PbS, Sphalerite ZnS, Piryte FeS_2, Markasite FeS_2, Smithsonite $ZnCO_3$, Cerrusite $PbCO_3$, Hemimorfite $Zn_4Si_2O_7(OH)_2 \cdot H_2O$, Native sulphur

Some of the speleothems studied are composed of hexahydrite in which Mg^{2+} ions are isomorphously replaced by Zn^{2+} and Fe^{2+}. Then their chemical composition is close to bianchite or ferrohexahydrite and they can form a solid solution (Kubisz, 1964). It is found that the examined hexahydrite minerals comprise Mn^{2+} isomorphic substitution which mainly occurs in chvaleticeite. Nevertheless, sulphate speleothems comprised of hexahydrite with numerous isomorphic replacements are unstable and show a general tendency towards transformations into pentahydrites.

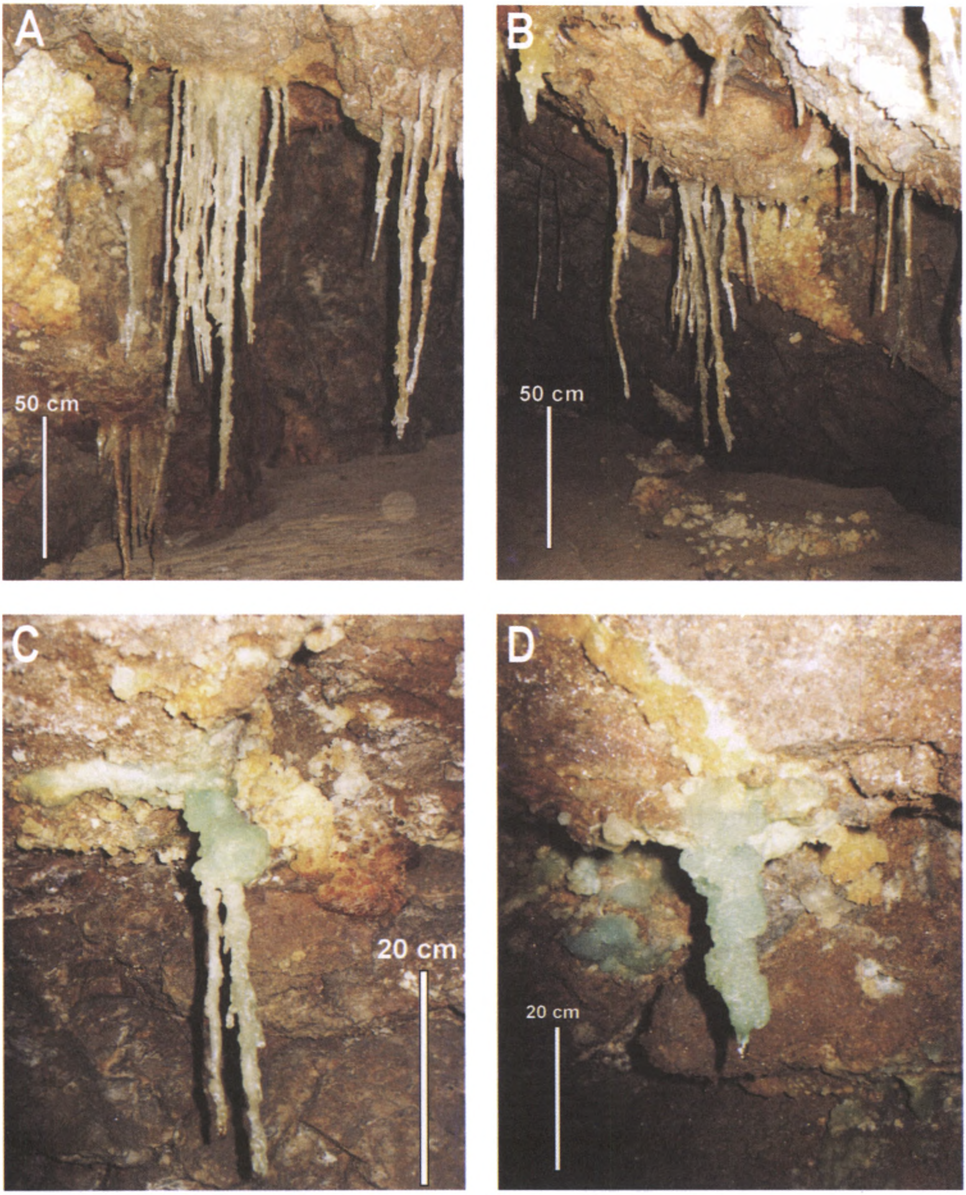
Dripstones consist mostly of Mg sulphates with a similarity in the composition of epsomite and a certain amount of Fe sulphates. The change in colours can be connected with draining and is one of the most common characteristics of sulphates occurring in speleothem, for example yellow and transparent epsomite (Phot. 1A, Phot. 2D) become white and light grey and their chemical compositions mainly include pentahydrite and hexahydrite.

In mining excavations melanterite can occur but its existence is strictly conditioned by a high level of humidity (Phot. 1C, D, Phot. 2C). Tints of melanterites are greenish and yellowish but in certain conditions connected with drainage, they change in colour to white and grey which seem to be similar to rozenite, which only in favourable conditions such as the excess of SO_4^{2-} ions, relative humidity ranging from 45% to 60% and a temperature of 19°C can become typical rozenite. Moreover, further decreases in humidity results in formation of szomolnokite. This mineral form is the result of pyrite and marcasite oxidation.

However, it can also form as a consequence of dehydration of melanterite. Other minerals such as ferrohexahydrite and siderotil can be found in dripstones including Fe-sulphates.

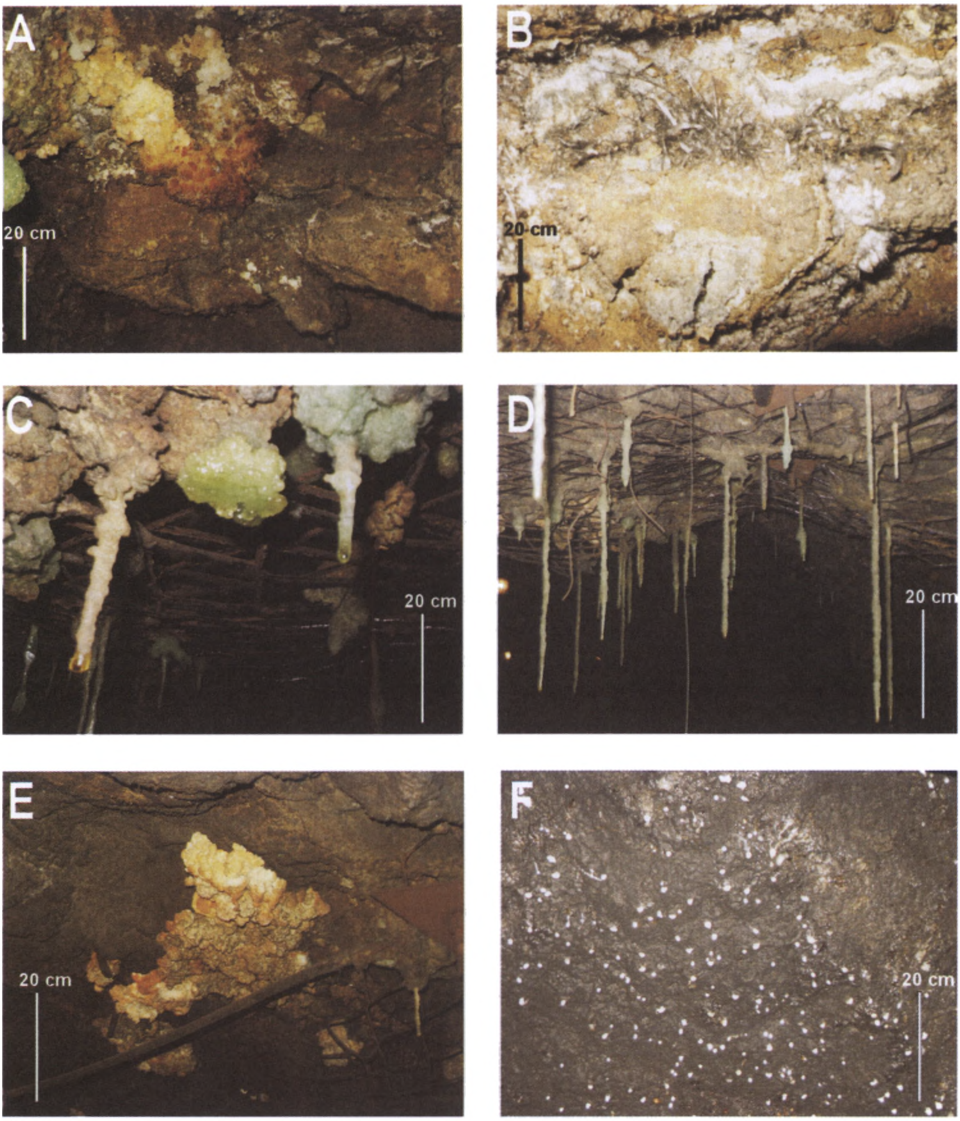
At present, there are five different hydrated Fe-sulphates which are widely known (Table 1). Their crystallization sequence begins successively with melanterite which is replaced by rozenite, szomolnokite, siderotil and ferric salt (Alpers et al., 1994, Jambor et al., 2000).

The mineral composition analysis of the examined samples shows that sulphate speleothems can be also connected with the hexahydrite and szomolnokite. It is assumed that copiapite forms as a secondary mineral after Zn-hexahydrite and thit is why it was called pseudo-copiapite (Kubisz, 1964). Copiapite occurs in Zn-Pb ores in forms of yellowish thin fine-crystalline efflorescence on the Zn-Fe sulfides. There are some other minerals appearing in paragenesis with copiapite such as smithsonite, cerussite, gypsum and hemimorphite. Light-yellow, powdery aggregates of copiapite are easily recognizable in secondary sulphate minerals. Similarily, intensive yellow tints are typical of fine-grained aggregates of Cd sulfides, like greenockite, which occurs in association with colloidal aggregates of sphalerite. Traces of Zn-sulphates such as bianchite and boyleite can be found in sulphate speleothems. Anglesite also occurs but in small quantities.



Phot. 1. Sulphate speleothems occurring in exploited excavations in the "Pomorzany" Zn-Pb mine
A – epsomite stalactites (white), **B** – epsomite stalactites (white), copiapite and ferrohexahydrite (yellow), **C** – a melanterite stalactite (green), copiapite and siderotile (yellow and red), **D** – a melanterite stalagmite

A large majority of the examined samples included a minute amount of crystalline gypsum, which forms in the presence of Ca^{2+} ions delivered by solutions from ore-bearing dolomite. In the investigated dripstones fine-crystalline gypsum grains reach up to 100 μ in size (Phot. 7). Isolated fine grains of sulfides represented by sphalerite, galena, pyrite, marcasite and native sulfur also occur in sulphate speleothems. Ore minerals were carried by waters from oxidation zones.



Phot. 2. Sulphate speleothems occurring in exploited excavations in the "Pomorzany" Zn-Pb mine
A – Mg-sulphates & Fe-sulphates, **B** – halotrichite, **C** – epsomite stalactites (white) and melanterite stalaktites (green), **D** – epsomite and melanterite stalactites, **E** – Fe-sulphates with rosenite and szamolnokite composition, **F** – blooms and efflorescence of Mg-sulphates with pentahydrite composition (white) formed in excavations where mining machines were used

Sulphate forms

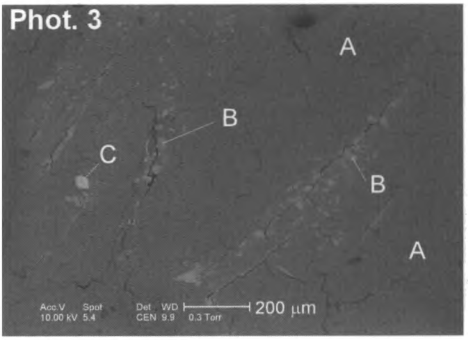
It is found that in some mining excavations of the "Pomorzany" Zn-Pb ore deposits the morphologically diversified sulphate speleothem are still forming mainly under the roof and on the side walls (Fig. 1).

Sulphate speleothems occur as stalactites, coatings, blooms, efflorescences and among the unusual forms are wire-like and hair-like ones. The largest stalactites are 3 m in length but they are rare and can only be observed in old exploited chambers of the mine. The most common occurrences are 20 to 30 cm (Phot. 1A, B, C, D). There is an inner channel in the structure of a stalactite called soda-straw, that is why sulfate water can be permanently delivered into the dripstones. The channels are 2 to 5 mm in diameter. However, soda-straw stalactites often appear in large aggregates or clusters of several pieces within one square metre (Phot. 2D). Some of the sulphate speleothems form 'cauliflower'-like clusters from a few cm to 50 cm in size which can fill cavities or fissures (Phot. 2A). Lowering of ambient humidity can cause the occurrence of sulphate crusts (Phot. 2A, C, E). These crusts cover the surface of side walls up to a few square metres in area. In excavations, where humidity is high, side walls and roofs are covered with thin coatings of fine-crystalline sulphates. The coatings are often tinted red by iron oxides. Concentrations of halotrichite, which occur as hair- or needle-shaped forms, can be found very rarely (Phot. 2B). The use of mining machines in some excavations also has an influence on the formation of dripstones. Then side walls are covered with tar from exhaust gases, whereas fine white oval sulphate minerals occur on the ceiling (Phot. 2F).

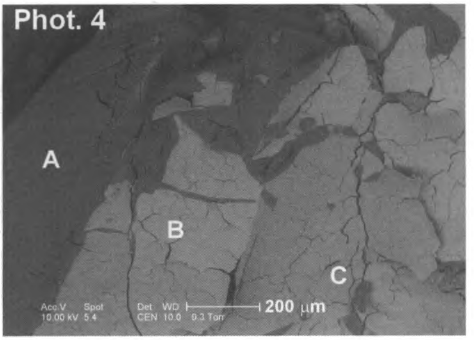
BSE and EDS methods used for identification of sulphate speleothems

Sulphate dripstones include secondary hydrated sulphates of magnesium and iron as well as Mg-Fe sulphates. Sometimes dripstones can significantly vary in chemical composition. This results from the fact that there are zones in dripstones in which sulphates are enriched with iron and zinc as well as zinc sulfides, lead sulfides and native sulphur (Phot. 3). These zones are highly developed in the vicinity of microcracks resulting in sulphate contraction connected with dehydration.

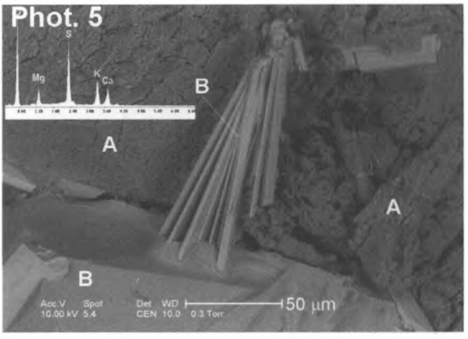
Most often Mg-Fe and Mg-Fe-K sulphates occur in the interior of dripstones, while on the outer part Mg sulphates are dominant. The latter can



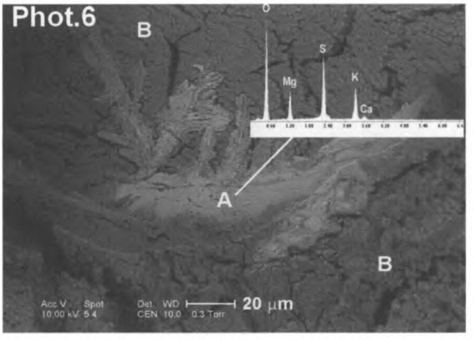
Phot. 3. Sulphate speleothems
A – Mg sulphate, **B** – Mg, Fe sulphate, **C** – native sulphur



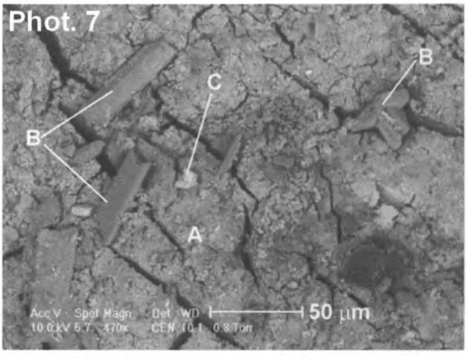
Phot. 4. Sulphate speleothems
A – Mg sulphate, **B** – Mg, Fe, K sulphate, **C** – Mg, Fe sulphate



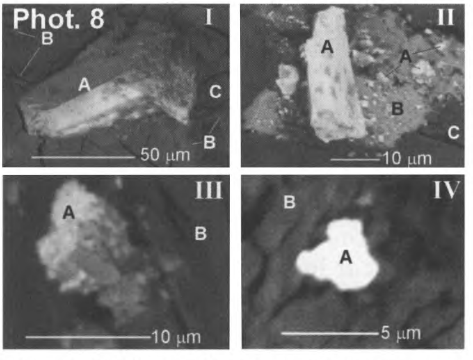
Phot. 5. Sulphate speleothems
A – Mg, Ca, K sulphates, **B** – Mg, Ca, K sulphates



Phot. 6. Sulphate speleothems
A – K, Mg sulphates, **B** – Mg sulphates



Phot. 7. Sulphate speleothems
A – Mg sulphate, **B** – Ca sulphate, **C** – Fe sulphate with Cl



Phot. 8. Sulphide minerals in sulphate speleothems
I: **A** – Zn sulphides, **B** – Zn sulphates, **C** – Mg sulphates, **II**: **A** – Pb sulphates & Pb sulphides, **B** – Zn sulphates & Zn sulphides, **C** – Mg sulphates, **III**: **A** – Sn oxide, **B** – Mg sulphates, **IV**: **A** – Pb sulphides & Pb carbonate with Ag

replace sulphates containing Fe and K in the fracturing and cleavage zones (Phot. 4).

Mg-Ca-K sulphates (Phot. 5) in the forms of fine cryptocrystalline aggregates (Phot. 5A) or automorphic crystals (Phot. 5B) can also be found in the dripstones. The crystals reach from 20 to 120 μm in size. The analyses of the crystal habit and EDS spectrums of these minerals indicate a chemical composition similar to hydrated sulphates such as polyhalite and syngenite (Phot. 5), which are recognizable among marine evaporite sediments. Mg-K sulphates also occur but they form single and isolated crystals of dendritic shapes on magnesium sulphates (Phot. 6).

During the study in the vicinity of Mg-K sulphates, fine-crystalline K-Cl salts were revealed, however, the traces of their occurrence in examined samples did not allow for the indentification of them using the X-ray method.

Table 2

Groups of minerals occurring in sulphate dripstones (EDS detected)

Primary minerals	Secondary minerals
Zn sulfide	Mg sulphates
Pb sulfide	Ca sulphates
Pb sulfide with Ag	Zn sulphates
Aluminosilicates K, Fe	Mg, Fe sulphates
Organic matter	Zn, Mg sulphates
Sn oxide	Mg, Ca, K sulphates
	Mg, K sulphates
	K, Mg, Cl sulphates
	Cu sulphates
	Pb carbonates
	Native sulphur

The sulphide speleothem in the "Pomorzany" Zn-Pb mine commonly consists of crystalline Ca sulphates (50–200 μm in size) occuring on the surface of Mg sulphates, they are typical gypsum forms (Phot. 7). Larger aggregates of gypsum occur in macro-porous Zn-Pb ores. The gypsum forms coatings on dolomites, sulfites and iron oxides and also fills microcracks and small cavities. Soon afterwards, on the surface of the gypsum other compounds such as Zn, Pb and Fe sulfides appear. The morphology and occurrence of sulfides indicate their secondary genesis.

Sulphate dripstones include fine-crystalline aggregates of primary sulfides of Zn and Pb (Phot. 8 I, II, III, IV). Grains of Zn-Pb sulfides reaching from 1 to 100 μm in size have crystalline forms. On the surface of Zn sulfide grains as well as in their close vicinity (Phot. 8 I), Zn sulphate crystallization takes place. These sulphates form fine-crystalline blooms and efflorescence grouping in the nucleus of crystallization in oval shapes (Phot. 8 I).

Pb sulfides occurring in the dripstones are fine-grained and often form poli-mineral aggregates with Zn sulfides. The surface of primary Pb sulfides is covered with sulphates and carbonates of Zn (Phot. 8 II). The dripstones in the Pomorzany Zn-Pb mine are characterized by an almost total lack of Fe sulfides and Fe oxides; iron occurs rather in hydrated sulphates of Fe and Mg-Fe. There are few microscopic aggregates of Sn oxides (Phot. 8 III), Cd carbonates, Pb sulfides and Pb carbonates with a high silver content (Phot. 8 IV) in the studied dripstones. Tiny submicroscopic organic matter appears on the surface of sulphates. Its source could be the Tertiary coals occurring in the deposit. In the examined dripstones tiny crystals of native sulphur can also be observed (Phot. 3). The chemical composition, the tint and structural features of sulphate minerals which were kept in laboratory condition for several months have changed. Melanterite dripstones, which are usually green or white in colour (Phot. 1C, D), when the water is released undergo a change into fine-crystalline rozenite or szomolnokite (Phot. 2E).

Heavy metals in sulphate speleothems

The chemical composition of the examined sulphate speleothems is diverse. They mainly include poli-mineral aggregates of hydrated sulphates of Mg, Ca, Fe, Zn (Table 1). The sulphate speleothems are characterized by different contents of heavy metals (Table 3). However, the study does not reveal lead in the sulphate speleothems, whereas the most significant amount of Fe, Zn, Cd and Mn occurs in the light green ones. The increase in zinc concentration is connected with the presence of boyleite and bianchite. A larger amount of zinc might cause cadmium occurrence but this metal is observed only in sulphates that contain zinc (Table 3).

A high percentage of Fe was observed when rozenite, siderotil and melanterite are present. Under oxidation conditions manganese ions can be activated that is why chvaleticeite is found. White and light reddish sulphate minerals comprise mainly Mg with a small amount of Ca. In these types of sulphates concentrations of zinc and iron are relatively low. It is found that transparent sulphates do not include heavy metals. They are comprised of almost mono-mineral concentrations of magnesium sulphates of the epsomite-hexahydrite-pentahydrite series.

Table 3

Heavy metals in sulphate speleothems (ASA analysis)

Sulphates dripstone	Zn	Pb	Fe	Cd	Mn
	[ppm]				
Sulphates (white)	227.7	2.3	139.8	3.9	23.8
Sulphates (light green)	11594	<2	78709.0	24.8	322.4
Sulphates (transparent)	<2	<2	9.0	4.3	<4
Sulphates (light red)	54.9	<2	402.5	3.7	26.5

Results and discussion

The excess of sulphate ions in waters draining Zn-Pb ore deposits results in actual formation of speleothems in mining excavations. The speleothems can form as a result of ore deposit oxidation affected by mining activities. The chemical composition of speleothems is determined by the mineral composition of ores, intensity of primary minerals solutions and humidity. The high humidity (92–95%) in mining headings is undoubtedly a necessary condition to form hydrated sulphate speleothems. A decrease in the humidity connected with changing of air flow direction in excavations or draining waters can result in slowing down the processes of sulphate speleothems formation.

The high oxidation-reduction potential and considerably higher humidity are favourable conditions for melanterite and epsomite formation. When ambient humidity is low (less than 80%) hepto- and hexo-hydrated sulphates can undergo transformation forming new hydrated sulphates such as pentahydrite, rozenite, starkeyite, szomolnokite and rarely copiapite. The most stable hydrate seems to be rozenite, whereas hexahydrite containing Zn^{2+} and Fe^{2+} replacements, which belong to the series of bianchite-ferrohexahydrite, are particularly unstable.

Prior to mining activity, in the first stage of drainage connected with dehydration of the rock mass, waters are characterized by relatively high flow intensity and comparatively low mineralization. Just after the deposit was drained residual oxidized descending waters infiltrate the ore-bearing layers in this way leaching ions such as SO_4^{2-}, Mg^{2+}, Ca^{2+}, Fe^{2+}, Fe^{3+} and Mn^{4+}. Solutions, which act as an initial stage for crystallized dripstones, comprise mainly Mg^{2+} and Fe^{2+}, minor ions of Ca^{2+}, Zn^{2+}, Pb^{2+} and K^- as well as traces of Cl^- ions.

The occurrence of native sulfur in speleothems can be connected with both the direct and indirect influence of certain bacteria on sulfides of Fe, Zn and Pb (Fowler et al., 2001). *Thiobacillus ferrooxidans* have been identified as playing significant roles in accelerating the oxidation of ferrous (Fe^{+2}) to ferric (Fe^{+3}) ion (Da Silva 2004, Edwards et al., 2000). The substantial impact of microorganisms on the development of sulphate reduction occurring in gypsum karst has been described by V.N. Andrejchuk and A.B. Klimchouk (2001).

In changeable conditions of humidity, the mineral composition of speleothems becomes unstable. During mining activity sulphates undergo dehydration which results in the formation of mono-mineral concentrations of Mg sulphates (Phot. 4). Older dripstones comprise mainly Mg sulphates.

A phase composition of the speleothems analysed in this study allowed researchers to determine the migration of certain metal ions due to acid drainage of rocks. Sulphate speleothems comprise minerals including heavy metals such as Fe, Zn, Pb as well as traces of Ag, Sn, Cu, the presence of which indicates the activation and migration of these metals under the conditions of chemical weathering stimulated by mining operations. Sediments in karst systems, which are developed in ore mining regions, can also be enriched with sulphates. Desulfurization and crystallization of sulphates can also be observed in waste piles containing sulfites and in soils contaminated with ores (Cabała et al., 2004a; Cabała, 2005).

Acknowledgements

We are grateful to Maria Dziurowicz for English translation and Michele Simmons who revised the English version of the manuscript.

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Jerzy Cabała, Grażyna Bzowska

Nacieki siarczanowe w kopalni cynku i ołowiu "Pomorzany", południowa Polska

Streszczenie

Podziemna eksploatacja rud Zn-Pb w kopalni „Pomorzany" jest prowadzona w zawodnionym, węglanowym górotworze. W horyzontach złoża objętych eksploatacją rozwijają się procesy utlenienia siarczków i kwaśnego drenażu skał (AMD). Dotlenione wody descenzyjne przesączające się przez dolomity kruszconośne ługują jony SO_4^-, Mg^{2+}, Ca^{2+}, $Fe(OH)^{2+}$, Fe^{2+}, Fe^{3+}, Zn^{2+} i Mn^{4+}. W wyrobiskach górniczych, kawernach krasowych, spękaniach i drobnych porach krystalizują uwodnione siarczany. Kolejność krystalizacji poszczególnych faz siarczanowych zależy od termodynamicznych warunków środowiskowych oraz składu chemicznego roztworów. W warunkach wysokiej wilgotności 92–95% w zakresie temperatur 10–20°C na stropie i ociosach wyrobisk tworzy się siarczanowa szata naciekowa. Tworzą ją zróżnicowane formy typu stalaktytów, stalagmitów, polew i wypełnień. Nacieki mają rozmiary do 1 m, są białe, żółtawe, czerwonawe lub zielonkawe. Budują je głównie siarczany Mg, Ca i Fe, siarczany zawierające Zn, Pb i Mn występują znacznie rzadziej. Metodami analizy rentgenowskiej rozpoznano uwodnione siarczany Mg i Ca, takie jak: starkeyit, pentahydryt, hexahydryt, epsomit i gips; siarczany Fe: szomolnokit, rozenit, syderotyl, ferrohexahydryt, melanteryt i kopiapit; siarczany Zn i Pb: boyleit, bianchit, anglezyt, oraz Mg i Mn: chvaleticeit. Obniżenie wilgotności prowadzi do dehydratacji siedmio- i sześciowodnych siarczanów oraz przejścia w fazy odpowiadające pentahydrytom, rozenitom, starkeitom, szomolnokitom, rzadko kopiapitom. W warunkach obniżonej wilgotności szczególnie nietrwałe są heksahydryty zawierające podstawienia Zn^{2+} i Fe^{2+}, należące do szeregu bianchit-ferroheksahydryt. Najtrwalszym hydratem siarczanu żelazawego jest rozenit. W naciekach rozpoznano submikroskopowe ziarna sfalerytu, galeny, markasytu, hemimorfitu, cerusytu i siarki rodzimej, występują także fazy zawierające Ag, Sn, Cu.

Siarczanowe formy naciekowe są indykatorem rozwoju kwaśnego drenażu skał prowadzącego do uruchomienia jonów metali w górotworze objętym eksploatacją. Krystalizacja nietrwałych, uwodnionych siarczanów Mg-Ca-Fe-Zn jest wywołana działalnością górniczą i wpływa na wzrost potencjału jonów metali i siarczanów transferowanych do wód podziemnych.

Jerzy Cabała, Grażyna Bzowska

Les spéléothèmes sulfatés dans la mine de zinc-plomb « Pomorzany »
dans le sud de la Pologne

Résumé

L'exploitation souterraine des gisements de Zn-Pb dans la mine « Pomorzany » est menée dans un orogène carbonate et aquifère. Dans les amas horizontaux exploités les processus d'oxydation des sulfures et le drainage minier acide (AMD). Des eaux oxydées descendantes transsudant par des dolomites ultramafiques dęcruent des ions SO_4^-, Mg^{2+}, Ca^{2+}, $Fe(OH)^{2+}$, Fe^{2+}, Fe^{3+}, Zn^{2+} et Mn^{4+}. Dans des excavations minières, cavernes karstiques, fissures et crevasses mineures se cristallisent des sulfates aquifères. L'ordre de la cristallisation des phases sulfates consécutives dépend des conditions thermodynamiques et de la composition chimique des

dissolutions. Dans les conditions de l'humidité élevée 92–95 % dans l'intervalle de 10–20°C sur le plafond et des piédroits se forme un plancher de spéléothèmes de sulfate. Ce sont des formes diverses de stalactites, stalagmites, calcites flottantes, remplissages. Les spéléothèmes atteignent les dimensions de 1m, et présentent des couleurs blanche, jaunâtre, rougeâtre ou verdâtre. Ces formes se composent avant tout des sulfates Mg, Ca et Fe, les sulfates contenants Zn, Pb et Mn sont beaucoup moins fréquents. A l'aide de l'analyse de Roentgen nous avons détecté des sulfates de Mg et Ca, comme: starkeyit, pentahydraté, hexahydraté, sel d'Epsum et gypse; des sulfates de Fe: szomolnokite, rozenite, siderotil, ferrohexahydrite, melanterite et ferricopiapite; des sulfates Zn et Pb: boyleite, bianchite, anglesite et des sulfates de Mg et Mn: de Chvaletice. L'abaissement de l'humidité conduit à la dehydratase des sulfates copperés et le passage aux phases correspondant aux pentahydratés, rozenites, starkeyits, szomolnokites, rarement copiapites. Dans les conditions de l'humidité abaissée des hexahydrites contenant des bases Zn^{2+} et Fe^{2+} – appartenant aux bianchites ferrohexahydrites – sont particulièrement peu durables. L'hydrate le plus durable est rozenite. Dans les spéléothèmes nous avons repéré des grains de soufre submicroscopiques tels que sphalérités, galènes, marcasites, hemimorphite, cérusite et le soufre, nous avons aussi noté des phases avec Ag, Sn, Cu.

Les spéléothèmes sont un indicateur du drainage minier acide qui mène à l'activation des ions de m étaux dans l'excavation exploitée. La cristallisation des sulfates peu durables, Mg-Ca-Fe-Zn est induite par l'activité de la mine et influence l'accroissement du potentiel des ions de métaux et de sulfates transférés dans des eaux souterraines.

First received: February 2006.

„Kras i Speleologia". T. 12 (XXI). Katowice 2008
Prace Naukowe Uniwersytetu Śląskiego nr 2537

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Hydrogeology of the Carboniferous – Devonian carbonate formation within the Upper Silesian Block

A b s t r a c t: The carbonate Carboniferous – Devonian rocks complex located within the Upper Silesian block has the thickness in the range from several hundreds to about 1460 m and the maximal depth of massif roof occurrence over 6000 m. It is heterogeneous, discontinuous and anisotropic one. There is observed a radical decrease of rock porosity and permeability with depth. Development of karstic forms within the carbonate complex depends on diversified history of the sedimentary basin geological evolution in the marginal and central parts of it.

In the area of the outcrops the carbonate rocks are strongly fractured and karstified. Investigations carried on in the central part of the basin under thick overburden of the sediments show that the carbonate rock mass is compact and it is practically impermeable. Higher porosity and permeability of the carbonate rock mass is observed only in the area of the uplifted Cieszyn tectonic block due to paleokarstification processes.

A hydrochemical zonation is observed within the carbonate formation. It is characterized by changes of mineralization, from 0.3 g/dm^3 to 223 g/dm^3, and chemical composition of water along flow routes.

Introduction

Within the Upper Silesian block in profile of the Paleozoic formation the carbonate series occurs. It consists of the Lower Carboniferous and Upper and Mid-

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dle Devonian rocks. This series in range of its occurrence is characterized by considerable diversification of hydrogeological environment what is connected with diversified geological and hydrogeological conditions.

The carbonate formation is poorly recognized geologically and hydrogeologically because of considerable depth of its occurrence within the Upper Silesian sedimentary basin. General characteristics of this formation hydrogeological environment presented in the paper is based on the results of the hydrogeological investigations carried on in not numerous boreholes situated in the southern and eastern parts of the Upper Silesian block.

Geological structure of the Upper Silesian block

The Upper Silesian block together with the Moravia block situated towards south-west constitute the bigger tectonic unit called Bruno-Vistulicum or Brunnia-Upper Silesia massif (B u ł a, 2000; K o t a s, 1985; Ż a b a, 1999). The Upper Silesian and Moravia blocks are separated by Haná fault zone (Fig. 1).

The Upper Silesian block laying on a crustal foundation is bordered by great, repeatedly active, tectonic zones (Ż a b a, 1999). Moravo-Silesian fold zone sepa-

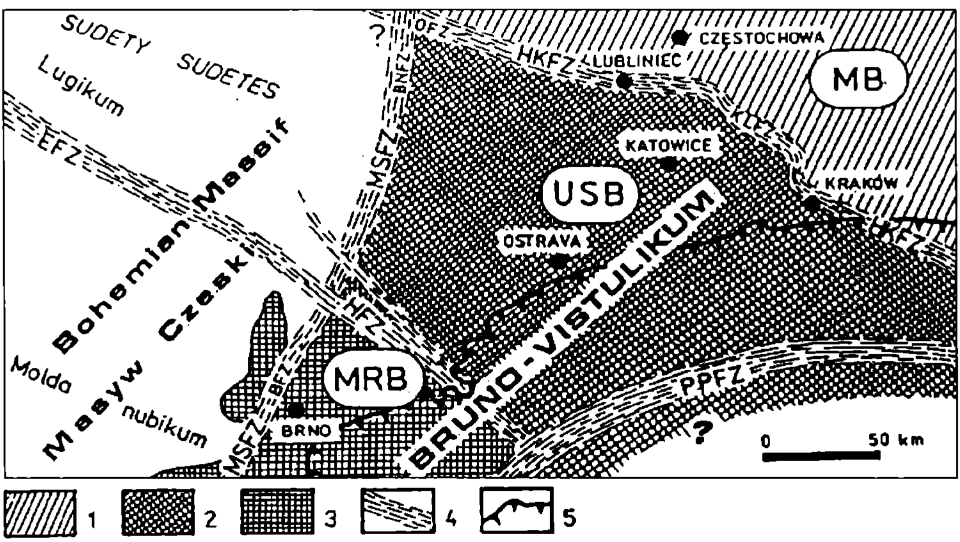

Fig. 1. Structural setting of the Upper Silesia Block (Ż a b a, 1999)

1 – Małopolska Block (MB), 2 – Upper Silesia Block (USB), 3 – Moravian Block (MRB), 4 – primary fault zones delimiting the Upper Silesia Block: HKFZ – Hamburg–Kraków Fault Zone (OFZ – Odra Fault Zone, KLFZ – Kraków–Lubliniec Fault Zone), MSFZ – Moravian–Silesian Fault Zone (BFZ – Boskovive Fault Zone, BNFZ – Brzeg–Nysa Fault Zone), EFZ – Elbe Fault Zone, HFZ – Haná Fault Zone, PPFZ – Peri-Pieninian Fault Zone; 5 – Carpathian overthrust front

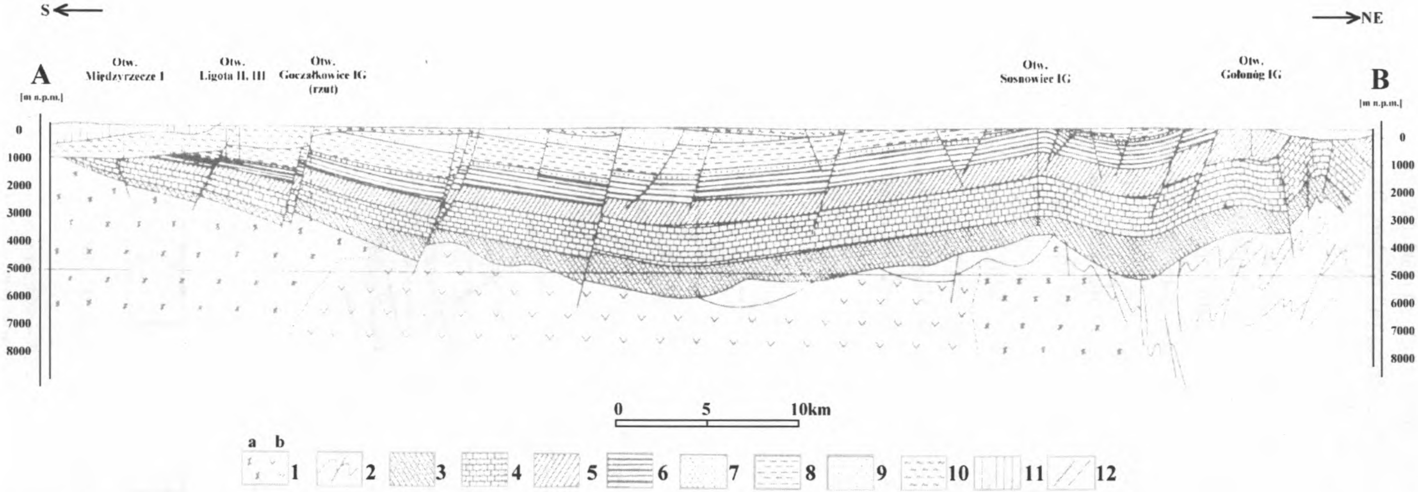

Fig. 2. Geological cross-section of the Upper Silesian Coal Basin (Kotas, 1994)

1 – crystalline basement: metamorphic and magmatic rocks, **2** – formations of Lower Paleozoic, **3** – clastic sediments formation of Lower Devonian, **4** – carbonate formations of Devonian and Lower Carboniferous, **5** – formation of marine clastic sediments, **6** – Paralic Series, **7** – Upper Silesian Sandstone Series, **8** – Mudstone Series, **9** – Cracow Sandstone Series, **10** – Miocene; **11** – **4** Carpathian flysch, **12** – faults and overthrusts rating the examined block from Bohemian massif constitutes its western boundary. The Cracow–Lubliniec fold zone bordering the Małopolska block constitutes its north-eastern boundary. Within range of the Upper Silesian block the Upper Silesian Coal Basin was developed (Fig. 1).

Geological structure of the Upper Silesian block was formed as a result of multiphase, superimposing one on another, sedimentary diastrophic activities of two orogenic cycles: Variscan and Alpine ones. The pre-Cambrian metamorphic and magmatic rocks of the Upper Silesian block covered by formations of the Cambrian clastic platform sediments constitute the older foundation (K o t a s, 1985). These sediments are direct base of the Variscan sedimentary cycle. The Upper Silesian Coal Basin was primarily formed as a result of sedimentary diastrophic activity of the Variscan cycle. Sedimentary cycle according to present knowledge is represented by terrigene sediments of Cambrian and Lower Devonian. The carbonate formation of Middle and Upper Devonian and Lower Carboniferous occurs above the terrigene formation (K o t a s, 1994). The Upper Carboniferous and locally Permian sediments occur stratigraphicly higher. The Mesozoic and Caenozoic cover formations occur on the folded sediments of the Variscan sedimentary cycle (Fig. 3).

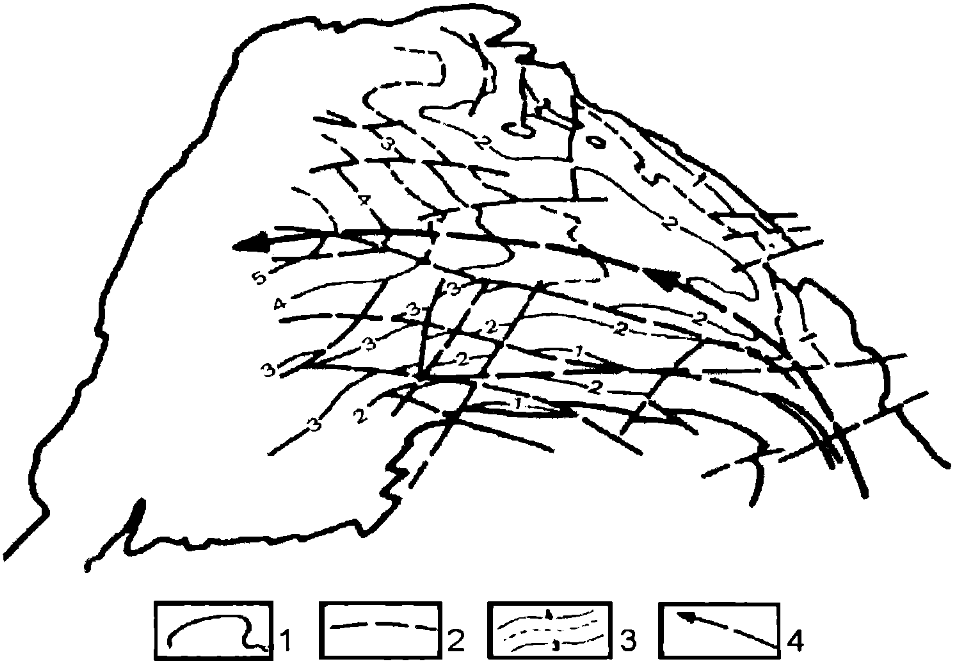

Fig. 3. Morphology of carbonate sediments roof of the Lower Carboniferous and Devonian (K o t a s, 1972).

1 – contemporary extent of productive deposits occurrence, 2 – more important tectonic dislocations, 3 – isolines of roof of carbonate sediments (4 = 4000 meters under sea level), 4 – axis of main synclinal structure and direction of its submerging

Tectonic reconstruction of the Upper Silesian block area took place as a result of sedimentary diastrophic activity of the Alpine cycle. The Tertiary subsidence structures filled with Tertiary molasse were formed within its southern and north-western parts. During the last stage of the Alpine cycle thrust of the Carpathians flysch over Miocene molasse took place within southern part of the Tertiary subsidence structure (Fig. 3).

Shape and discontinuities of the Variscan formation base and situation of the block within the frames of the Variscan fold zones: Moravio-Silesian and Cracow–Lubliniec ones had decisive influence on style of structure of the considered tectonic unit. The Variscan folding as well as rejuvenescence and rebuilding of older tectonic forms by the Alpine orogeny played basin part in forming of contemporaneous tectonic structures of the Upper Silesian block (Kotas, 1994). Geological structural factors caused considerable diversification of thickness and depth of occurrence of the Paleozoic formations among them carbonate complex of Lower Carboniferous – Devonian within the Upper Silesian block (Fig. 2, 3).

Carboniferous – Devonian carbonate formation

The Carboniferous – Devonian carbonate formation of the Upper Silesian block occurs the most shallowly within the eastern margin of sedimentary basin in the area of Cracow–Lubliniec folded zone where it is partly uncovered (Fig. 2, 4). In the zone of the under-Tertiary outcrops in region of Bielsko-Biała–Kęty roof of the formation is at the depth of 800–1400 m. In Goczałkowice it reaches the depth of 1900 m and in Sosnowiec 1640 m. The maximal depth of roof formation occurrence in the central part of the Upper Silesian block passes 9000 m (Kotas, 1994). The stated thickness of the formation is in range from several hundreds to about 1460 m.

The Middle and Upper Devonian formations (Famenian, Frasnian) as well as the Lower Carboniferous ones (Visean, Tournai) recognized by deep boreholes: Maczki IG-1, Sosnowiec IG-1, Goczałkowice IG-1, Kozy MT-3, Ustroń and in region Kęty–Bielsko-Biała–Andrychów, are represented by limestone and dolomitic limestone with intercalation of claystone, mudstone and marl, locally sandstone and breccia. The carbonate formation is split (Kotas, 1985). In the roof links limestone but in the floor links dolomite dominate. The carbonate rocks are compact and fractured. However these fractures are generally scarred over with calcite like the majority of not numerous small caverns. In the area of Cieszyn block in the southern marginal part of the Carboniferous sedimentary basin there are observed more numerous fractures and caverns within the carbonate formation.

In the eastern marginal folded zone of the Upper Silesian block the Devonian and Lower Carboniferous carbonate rocks are stated in area of Krzeszowice and Siewierz, Zawiercie and Klucze (Fig. 4). They are represented by organogenic, organodetrital and micritic limestone as well as dolomitic limestone and dolomite. Investigations and observations carried on in the boreholes in region of Siewierz, Zawiercie, Klucze, Niegowonice and before all in the Lower Carboniferous limestone deposits in Czatkowice quarry show that carbonate rock massif, especially shallowly deposited, is strongly fractured and cavernous. Typical karstic forms like sinkholes, karstic channels, joint fissures, vertical caves, are observed there.

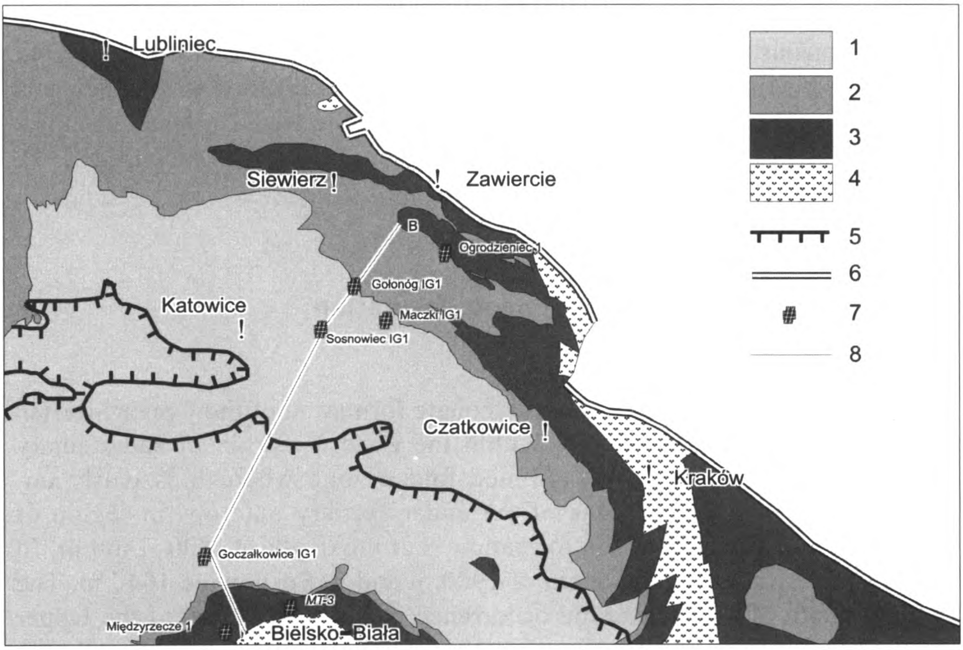

Fig. 4. Geological sketch of the Palaeozoic (without Permian and younger deposits) of the Upper Silesian Block eastern part (simplified after Z. Buła, 2000).
1 – coal-bearing Upper Carboniferous deposits of the Upper Silesian Coal Basin (Westfalian A–D and Namurian A–C), **2** – clastics deposits – Culm (Visean and Namurian A), **3** – mainly carbonate deposits – (Lower Carboniferous – Tournaisian – Viséan and Devonian), **4** – Lower Palaeozoic and Precambrian deposits, **5** – aproximate extent of the Miocene deposits overlying the top of the Carboniferous, locally Devonian and Cambrian strata, **6** – Kraków–Lubliniec tectonic zone, **7** – the chosen boreholes, **8** – geological cross-section line (A – B)

Hydrogeological characteristics of the Upper Silesian Basin

Within the frames of the Upper Silesian block a sedimentary basin with thickness of sediments reaching 11 km is formed. This basin is filled in with sediments ranging in age from Cambrian to Quaternary inclusively. Knowledge of paleogeographical and paleogeological conditions of sedimentary basin development enables division into seven hydrogeological cycles in its development history (Różkowski, Przewłocki, 1979). Within the frames of each cycle two stages occur: the sedimentary one connected with sediments accumulation and the infiltrational one connected with denudation and intensive alimentation of aquifers by atmospheric precipitation. The infiltrational stage was a period of intensive karstification of the carbonate massif.

The Upper Silesian basin is characterized by occurrence within its hydrogeological profile horizons and aquifers of different age which are insulated one from another by impermeable sediments. The Lower Carboniferous and Devonian carbonate sediments are considered as one aquifer (hydrogeological water-bearing complex) on account of hydraulic bond of waters and common hydraulic structure.

The Upper Silesian basin is in the rank of the local hydrogeological region called the Upper Silesian region (Różkowski, 1991). Within range of this region two sub-regions are distinguished: the north-eastern one (I) and the south-western one (II). Both sub-regions have distinct tectonic foundation, diversified geologic structure and different recharge conditions of the Paleozoic aquifers. The north-eastern sub-region is the regional recharge zone of the Paleozoic aquifers on account of its elevated situation and hydraulic contact among aquifers of Quaternary, Mesozoic and Paleozoic occurring there. In conditions of favouring hydrogeological configuration it concerns also the Carboniferous Devonian carbonate aquifer. The sub-region II occurring within range of the Alpine subsidence structures is the area where high piezometric pressure within the discussed formation are formed.

Hydrogeological properties and water-bearing capacity of the Carboniferous – Devonian carbonate formation

The calcerous dolomitic hydrogeological complex is heterogenous, discontinuous and anisotropic one. Anisotropy of the rock mass is connected with system of karstic fracturing and caverns which occur particularly distinctly within the eastern margin of the Upper Silesian block. Hydraulic structure of the carbonate massif consists of three hydraulic systems: porous, fissured and karstic ones. They are characterized by transmissivity and hydraulic capacity of rock massif and their measure are the values of hydraulic conductivity, effective porosity and water-bearing capacity.

Laboratory and field examination of hydrogeological properties of the carbonate formation rocks shows considerable diversification of their values within zone of the carbonate formation outcrop (sub-region I) and at the great depth of its occurrence (sub-region II). There is observed a radical decrease of rock porosity and permeability with depth. This phenomenon is connected with rock mass diagenesis process and different geological history of sedimentary basin development.

In the area of outcrop the carbonate formation rocks are strongly fractured and karstified what was distinctly observed among others in the boreholes Grabowa and Pomorzany 2. Well discharge is in general in order of some scores of cubic meters per hour with depression of dozen or so meters. Average values of hydraulic conductivity obtained from test pumping are in order of 10^{-6}–10^{-5} m/s indicating medium permeable rocks. Investigations of the Lower Carboniferous limestone and dolomite carried on by T. Leśniak and J. Motyka (1991) in area of Czatkowice show that value of rock matrix open porosity is in range of 0.0013 to 0.157 (average 0.024). Average coefficient of porous space permeability is 9.64×10^{-11} m/s. Representative coefficient of fissure permeability is about 1.1×10^{-5} m/s. (Leśniak, Motyka, 1994). From the mentioned investigations results that the hydraulic net of fissures and caverns plays the basic part in water conduction within the eastern margin zone of the carbonate formation occurrence. Factor determining degree of rock mass permeability is there density of fissures occurrence and width of their opening as well as frequency of karstic voids, their diameter and degree of their filling.

High degree of carbonate massif permeability within the mentioned zone should be connected with long periods of denudation process during infiltrational hydrogeological cycles. Development of karstic forms studied by T. Leśniak and J. Motyka (1991) in the Lower Carboniferous limestone in Czatkowice quarry shows occurrence of two stages of karstification. The first one took place in turn of Permian and Triassic after the Variscan tectonic movements ending with the Upper Jurassic transgression. The second younger stage of karstification started after retreat of the Jurassic sea and it persists with small interruptions until today.

Taking into account hydrogeological conditions of the margin zone of the carbonate formation occurrence it should be stated that this area is situated within the active water exchange zone where average velocity of water flow through three-porous hydraulic net of the carbonate rock mass is in range of several hundreds meters per year reaching some kilometers per year.

Investigations carried on within the sub-region II in the boreholes Goczałkowice IG-1, Sosnowiec IG-1 and Maczki IG-1 show that in the central part of the basin under thick overburden of the Upper Paleozoic and Tertiary sediments the carbonate rock massif is compact and it is practically impermeable (Różkowska, Różkowski, 1973; Dembowski, Różkowski, 1967; Kotas, Różkowski, 1973; Różkowski, Chmura, 2001). Primary porosity dominates in the hydraulic system of the rock complex. Fissures and caverns are generally scarred over with calcite. But fissure system can locally slightly conduct water.

Open porosity of porous space determined by laboratory tests is in range from 0.001 to 0.054. But for 85% of examined samples of limestone values of this parameter are less than 0.01 and for dolomite 0.02. Geophysical logging indicates increase of open porosity coefficient values of dolomites to 0.02–0.06. Determination of carbonate rock permeability by laboratory tests shows that taking into account entirely porous space these rocks are practically impermeable (under 1.0×10^{-9} m/s). Maximal locally found permeability calculated as a coefficient of permeability is 1.6×10^{-8} m/s.

Insignificant water-bearing capacity of the carbonate formation is presumed on the base of observation of slight salinity of drilling fluid during drilling as well as hydrogeological investigations carried on in the mentioned boreholes. In case of Goczałkowice IG-1 local inflow of brine to the borehole after perforation was in range to some scores of liters per 24 hours. After acid treatment of rock massif this inflow in test pumping increased to 400 liters per hour with depression about 250 m.

Risen cavernity of rock mass was observed nearby surface plane of discrepancy of the Carboniferous flysch and the carbonate formation within range of the zone of the old pre-Upper Visean denudation surface. Watching paleogeological development of the Upper Silesian basin it should be supposed that in its central part the Carboniferous Devonian carbonate formation could not be subjected to farther intensive denudation processes and rock karstification.

Geological development of the Upper Silesian basin within its marginal southern part in range of the Cieszyn block took place in a different manner. It is an area of tectonicly elevated part of the basin where the Upper Carboniferous sediments are strongly reduced or where there is lack of them. It concerns the Mesozoic sediments too. Only sediments of the Tertiary molasse occurring within roof of the Paleozoic formation are well developed (Fig. 3, 4).

Increased rock massif porosity and permeability observed there within the Carboniferous – Devonian carbonate formation is a result of old (buried) karstic and other weathering processes (Michalik, 1973a; Oszczypko, 1981) which took place within geological history of this area. Occurrence of the Devonian limestones karstification processes was observed among others in the boreholes: Ustroń 3, Kęty 7 and 8, Kozy MT-3. Phenomenon of paleokarst within the carbonate formation is of regional scale. During the Upper Carboniferous, Permian and whole Mesozoic periods the elevated region of the Cieszyn block as a land was eroded and the carbonate formation was karstified (Michalik, 1973b). Denudation of the carbonate formation processes were interrupted by the Miocene sea transgression. The oldest signs of karstification were observed within the Middle and Upper Devonian sediments beneath the Lower Carboniferous formation. In the boreholes (Potrójna IG-1, Ustroń IG-2 and IG-3, Kęty 7 and 8) beneath the Lower Carboniferous sediments there was observed significant leak of drilling fluid but during sampling of these horizons influx of brines was observed. Investigations carried on by N. Oszczypko (1981) show that the Carpathian Foreland with the Cieszyn block region before Lower Badenian was an area leveled to a high degree and subjected to denudation processes. Groundwater within rock mass was sweetened off to the depth of several hundreds meters.

Reservoir properties of the carbonate formation of the Cieszyn block region were recognized in some scores of prospect boreholes of oil industry as well in the boreholes drilled for therapeutic water prospecting and of mine brines subsurface injection. Especially the last ones Krasna IG-1 (Niemczyk et al., 1994) and Kozy MT-3 (Chowaniec, Wątor et al., 1997) examined in detail gave new data for recognition of reservoir properties of the carbonate formation and its water-bearing capacity. They show that within range of the Cieszyn block the carbonate formation can be characterized by increased permeability and water-bearing capacity because of occurrence of secondary porosity connected with fracturing and cavernity of rocks.

Laboratory examinations of core samples show that carbonate rocks are practically impermeable. Coefficient of porosity is in range of 0.00–0.042, usually below 0.01. According to geophysical logging value of zone porosity can reach 0.05. Permeability of rocks in light of laboratory examinations is generally very low, below 1×10^{-9} m/s, locally reaching 1.5×10^{-8} m/s. These results confirm previous supposition that zones of secondary porosity it means zones of open fissures and karstic caverns form a basic factor of the carbonate formation permeability and water-bearing capacity increase.

Similar observations were particularly done in the boreholes Krasna 1 and Kozy MT-3. The zones of non scarred over rock mass fissurity and cavernity determined on a base of geophysical logging after sampling by subsurface samplers shown increased rock permeability which reached 1.04×10^{-7} m/s and inflow was in range 10.8–41.3 m^3/h. The tests of subsurface injection run after acid treatment within the interval of the length of 57 m shown great water-bearing capacity of rocks reaching 90 m^3/h with injection pressure about 20 MPa (Niemczyk et al., 1994).

Influence of secondary porosity on increase of permeability and water-bearing capacity of the carbonate formation was confirmed also by examinations carried on in the borehole Kozy MT-3 (Chowaniec, Wątor et al., 1997). Rock massif was characterized by average open porosity 0.034. Permeability of porous space examined in laboratory reached maximal values 1.1×10^{-8} m/s. Coefficient of permeability during test pumping was in order to 10^{-9} m/s. Its value after acid treatment increased to 4×10^{-7} m/s.

Discharge of borehole during test pumping was 41.4 m^3/h, drawdown 93.5 m. Water-bearing capacity before acid treatment was 71 m^3/h with injection pressure 13 MPa. After acid treatment this value increased to 180 m^3/h with injection pressure about 4.5 MPa.

Chemistry of water and chemical zonation of the carbonate formation

The hydrochemical zonation characteristic for sedimentary basins is observed within range of the Carboniferous Devonian carbonate formation. The mentioned regional zonation is characterized by changes of mineralization and chemical composition of waters along their flow routes. A general tendency of water mineralization growth as well as changes of its ionic composition (according to sequence $HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 \rightarrow SO_4 + Cl \rightarrow Cl$) with depth is observed.

A base for division into hydrochemical zones within the carbonate formation is occurrence of two types of waters of different origin and time of stay in rock massif what is documented by examination of their isotopic composition. In light of present knowledge it should be assumed that beside contemporaneous infiltrating waters which occur in the eastern marginal part of the recharge area there exist buried waters mainly paleoinfiltrational ones in the central part of the Upper Silesian basin. Mixed waters of these two mentioned types form the transitional zone. The presented model is probably more complicated because of insufficient recognition of hydraulic contacts between the carbonate formation aquifer and surrounding it ones as well as diversified origin of buried waters.

Within the sub-region I in the zone of the carbonate formation recharge area a hydrochemical zonation is marked by transition from waters of hydrochemical type HCO_3-Ca-Mg to waters of types HCO_3-SO_4-Ca-Mg and SO_4-Ca-Mg, SO_4-Cl-Ca-Mg when mineralization ranges from 0.3 to about 4 g/l.

Characteristic chemical composition of water sampled from exploited wells expressed by Kurlov formula is as follows:

$$M^{0,6}\frac{HCO_3^{80,8},\ SO_4^{14,9},\ Cl^{4,3}}{Ca^{57,4},\ Mg^{35,1},(Na+K)^{7,5}}.$$

The mentioned waters are slightly alkaline. Value of pH is in range 6.9–7.8. Physico-chemical processes between carbonate sediments and circulating waters form mineralization and chemical composition of waters. Nitrogen and oxygen dominate in gaseous composition of waters what indicates occurrence of them within oxidation zone. Intensity of hydrochemical transformation depends before all on geochemical environment, flow routes and filtration velocity as well as covering degree of the Carboniferous – Devonian carbonate formation.

Water chemistry is formed within the zone of active exchange of ground- and surface-waters. It is confirmed by water chemistry and its isotopic composition. Positive tritium values and values of stable isotopes rate $\delta^{18}O$ –10.46 and δD –71.5 promille show that they are young Holocene waters.

Great flow velocity and easiness of water exchange affect on short time of water contact with rock massif and good rock washing. Circulation conditions are less favouring under increased overburden and it results in increase of water mineralization and change its chemical composition with depth.

Within the hydrochemically recognized deep part of the Upper Silesian basin (sub-region II) in the carbonate formation aquifer there occur brines of Cl-Na and Cl-Na-Ca types with mineralization from 63 to 223 g/l. Increase of water mineralization and basic ions concentration with depth is observed. Brines pH value is in range 5.3 to 7.2. Total hardness is in order of 36 400 mg $CaCO_3/dm^3$. Chemical composition of brines expressed by Kurlov formula is as follows:

$$J^{4.3-48.6}Br^{356.6-586.0}\,M^{63.15-223.59}\frac{Cl^{98.49-99.70}HCO_3^{\,0.02-3.7}\,SO_4^{\,0.00-0.48}}{Na+K^{63.89-79.35}Ca^{16.02-31.89}Mg^{2.16-10.86}}$$

The values of hydrochemical indices are as follows: rNa/rCl = 0.64–0.80; $rSO_4 \times 100/r$Cl = 0.14–1.44; $rSO_4 + HCO_3/r$Cl = 0.002–0.015. These values indicate high degree of water metamorphism and occurrence of brines within reductive environment in the zone of hydrodynamic stagnancy. Good insulation of buried brines and their stagnant character as well as their paleoinfiltrational origin are confirmed by results of their stable isotope composition examinations: $\delta^{18}O$ – 1.98, δD – 15.9 promille (Różkowski, Przewłocki, 1974; Zuber, Pluta, 1989).

Brines are characterized by increased concentrations of iodide, bromine and iron. Concentration of bromides is in range 127–586 mg/dm^3. This concentration increases with depth. Iodides occur in brines in concentration 3–48 mg/dm^3. It should be underlined increased concentration of radionuclide ^{226}Ra in examined brine in MT-3 borehole (34.663 kBq/m^3).

Within gaseous composition of brines dominates methane. The lower concentrations of higher hydrocarbons within clean gaseous composition suggest their origin mainly from degassing of carbonized organic remnants and it allows to number them among non-gasoline gases. Maximal concentrations of hydrocarbons with great amount of CO_2 at the same time was found in the boreholes Goczałkowice IG-1 and Sosnowiec IG-1. Great concentration of CO_2 indicates occurrence of intensive processes of hydrocarbons destruction in past (Kotas et al., 1973).

Conclusions

The carried on studies show significant diversification of hydrogeological environment of the Carboniferous – Devonian carbonate formation occurring within range of the Upper Silesian block. This environment is formed in conditions of diversified geological structure of the Upper Silesian block and different development of geological processes within the marginal and central parts of the Upper Silesian sedimentary basin. Geological structure controls forming of hydrodynamic and hydrochemical fields within the Upper Silesian basin and it influences also on diversification of basic hydrogeological parameters of the carbonate formation aquifer. It concerns especially hydrogeological properties and water-bearing capacity of the formation, chemical composition of groundwaters and also residence time in rock massif.

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Środowisko hydrogeologiczne karbońsko-dewońskiej serii węglanowej bloku górnośląskiego

Streszczenie

Utwory serii węglanowej dewonu środkowego i górnego oraz karbonu dolnego, rozpoznane w zasięgu bloku górnośląskiego nielicznymi głębokimi otworami, są reprezentowane przez wapienie i wapienie dolomityczne oraz dolomity. Seria węglanowa ma swe wychodnie na obszarze krakowsko-lublinieckiej strefy uskokowo-fałdowej, osiągając maksymalną głębokość swego występowania (ok. 6000 m) w centralnej części bloku górnośląskiego. Stwierdzone miąższości serii wahają się w granicach od kilkuset do ok. 1460 m (Kotas, 1994).

Ośrodek hydrogeologiczny kompleksu węglanowego jest niejednorodny, nieciągły i anizotropowy. Sieć hydrauliczna ośrodka skalnego składa się z trzech systemów hydraulicznych: porowego, szczelinowego i krasowego.

Na obszarze wschodnich wychodni widać silnie spękane i skrasowiałe skały serii węglanowej. Wydajności studni są na ogół rzędu kilkudziesięciu m^3/h przy kilkunastumetrowych depresjach, a średnie wartości współczynników filtracji, uzyskane z próbnych pompowań, są rzędu 10^{-6}–10^{-5} m/s (Leśniak, Motyka, 1991).

Badania prowadzone w otworach Goczałkowice IG-1, Sosnowiec IG-1 i Maczki IG-1 wykazały, że w centralnej części basenu pod miąższym nadkładem utworów młodszego paleozoiku

i trzeciorzędu górotwór serii węglanowej wykazuje szczelność i praktyczną nieprzepuszczalność (Różkowska, Różkowski, 1973; Dembowski, Różkowski, 1967). Szczeliny i kawerny z reguły są zabliźnione kalcytem. Współczynniki filtracji kształtują się poniżej 1,0 × 10^{-9} m/s, dopływy solanki zaś do otworu po kwasowaniu górotworu osiągają maksymalne wartości 0,4 m^3/h przy depresji ok. 250 m.

Korzystniej kształtują się parametry hydrogeologiczne serii węglanowej w zasięgu tektonicznie wyniesionej kry cieszyńskiej, położonej w południowej części bloku górnośląskiego. Karbońsko-dewoński kompleks węglanowy charakteryzuje się podwyższoną porowatością i przepuszczalnością, co jest następstwem występujących tu starych (kopalnych) procesów krasowych i innych procesów wietrzeniowych (Michalik, 1973b; Oszczypko, 1981).

Zasadniczy wpływ na podwyższenie przepuszczalności i wodonośności górotworu węglanowego mają strefy wtórnej porowatości, tzn. strefy drożnych, niewypełnionych szczelin oraz pustek krasowych. Opróbowania próbnikiem złoża wykazały podwyższoną przepuszczalność skał, dochodzącą do 1,04 × 10^{-7} m/s, oraz dopływy rzędu 10,8–41,4 m^3/h. Wydajności otworów po kwasowaniu wzrastały do ponad 100 m^3/h (Chowaniec, Wątor i in., 1997).

W zasięgu karbońsko-dewońskiego kompleksu węglanowego obserwuje się występowanie regionalnej strefowości hydrochemicznej, charakteryzującej się wzrostem mineralizacji, od 0,3 g/dm^3 do 223 g/dm^3, oraz zmianą składu chemicznego wód. W strefie zasilania zaznacza się ona przejściem od wód typu HCO_3-Ca-Mg do wód typu HCO_3-SO_4-Ca-Mg oraz SO_4-Ca-Mg i SO_4-Cl-Ca-Mg. W głębokiej części basenu górnośląskiego, w kompleksie wodonośnym serii węglanowej, występują solanki typu Cl-Na i Cl-Na-Ca, o mineralizacji od 63 g/dm^3 do 223 g/dm^3. Wartości wskaźników hydrochemicznych: rNa/rCl = 0,64–0,80; rSO_4 × 100/rCl = 0,14–1,44; rSO_4 + HCO_3/rCl = 0,002–0,015, wskazują na wysoki metamorfizm wód i występowanie solanek w środowisku redukcyjnym. Wartości izotopów trwałych: $\delta^{18}O$ –1,98, δD –15,9 promili, wskazują na paleoinfiltracyjne pochodzenie wód (Różkowski, Przewłocki, 1974).

Andrzej Różkowski, Jacek Różkowski

Le milieu hydrogéologique de la série des carbonates du carbonifère – dévonien du block de la Haute Silésie

Résumé

Les formations de la série des carbonates du dévonien moyen et supérieur et le carbonifère inférieur, dénotées dans l'étendue du bloc de la Haute Silésie par des orifices peu nombreux mais profonds, sont représentées par des calcaires et des calcaires dolomitiques et des dolomites. La série des carbonates a ses gîtes sur le terrain de la zone de pli-seuil de la région krakowsko-lubliniecka, en atteignant le maximum de sa profondeur (environ 6000 m) dans la partie centrale du bloc de la Haute Silésie. On constate les épaisseurs de la couche aquifère de la série entre quelques centaines à 1460 m (Kotas, 1994).

Le milieu des eaux souterraines est non homogène, non continu et anizotrope. Le réseau d'écoulement du milieu rocheux se compose de trois systèmes hydrauliques: poreux, fissuré et karstique.

Sur le terrain des gîtes d'est des roches de la série des carbonates sont fortement fissurés et karstiques. Les débits potentiels des puits sont d'habitude de quelques dizaines m^3/h avec des dépressions de quelques mètres. Des valeurs moyennes du taux d'infiltration, obtenues au cours du pompage des puits égalent à 10^{-6}–10^{-5} m/s (Leśniak, Motyka, 1991).

Les recherches menées dans des puits de Goczałkowice IG-1, Sosnowiec IG-1 et Maczki IG-1 démontrent que dans la partie centrale du bassin, sous le recouvrement des formations du

paléozoïque supérieur et du tertiaire, l'orogène présente une étanchéité et une imperméabilité entière (Różkowska, Różkowski, 1973; Dembowski, Różkowski, 1967). Les fissures et les cavernes sont d'habitude cicatrisées par le calcite. Les coefficients de filtration se placent au-dessus de $1,0 \times 10^{-9}$ m/s, et le débit entrant de saumure dans le puits après l'acidification de l'orogène atteint au maximum 0,4 m^3/h avec la dépression d'environ 250 m.

Les paramètres hydrologiques de la série carbonate dans l'étendue de la plaque de Cieszyn, élevée tectoniquement et placée dans la partie sud du bloc de la Haute Silésie, se présentent plus favorablement. Le complexe des carbonates du carbonifère – dévonien se caractérise par une porosité élevée et une étanchéité ce qui est le résultat de vieux (fossiles) processus karstiques et d'autres processus d'érosion (Michalik, 1973b; Oszczypko, 1981).

Influence principale sur l'accroissement de la perméabilité et la capacité d'être aquifère de l'orogène carbonate démontrent des zones de la porosité secondaire c'est-à-dire des zones des fissures pénétrables et vides et des vides karstiques. Les tests effectués avec un échantillonneur de la pierre ont prouvé une perméabilité des roches relevée jusqu'à $1,04 \times 10^{-7}$ m/s et des débits entrant de 10,8–41,4 m^3/h. Les débits potentiels des puits après l'acidification montaient jusqu'à 100 m^3/h (Chowaniec, Wątor et al., 1997).

Dans l'étendue du complexe des carbonates du carbonifère – dévonien on observe une zonalité hydrogéologique régionale caractérisée par un accroissement de minéralisation de 0,3 g/dm^3 à 223 g/dm^3 et par le changement de la composition chimique des eaux. Dans la zone d'alimentation il est marqué par le passage des eaux du type HCO_3-Ca-Mg aux eaux du type HCO_3-SO_4-Ca-Mg et SO_4-Ca-Mg et SO_4-Cl-Ca-Mg. Dans la partie profonde du bassin de la Haute Silésie, dans le complexe d'ensemble d'aquifères de la série des carbonates on observe des saumures type Cl-Na et Cl-Na-Ca avec la minéralisation de 63 g/dm^3 à 223 g/dm^3. Les grandeurs des indices hydrochimiques: rNa/rCl = 0,64–0,80; $rSO_4 \times 100/r$Cl = 0,14–1,44; $rSO_4 + HCO_3/r$Cl = 0,002–0,015 démontrent une grande transformation de la composition chimique des eaux souterraines et de la présence des saumures dans le milieu réducteur. Les valeurs des isotopes stables $\delta^{18}O$ –1,98, δD–15,9 promilles confirment la paléo-infiltration comme la source originale des eaux (Różkowski, Przewłocki, 1974).

First received: February 2002.

„Kras i Speleologia". T. 12 (XXI). Katowice 2008
Prace Naukowe Uniwersytetu Śląskiego nr 2537

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Drinking water supply from karst water resources (the example of the Pivka basin, SW Slovenia)

Abstract: Postojna water supply provides drinking water to households and industry in Postojna and Pivka municipalities. Its most important source is the Malenščica river spring. Some water is added by karst springs under Nanos Mountain. A basic question of drinking water supply in Pivka basin is how to assure a suitable water quality and how to reduce water losses in the water supply network.

Inadequate upkeep of the old pipelines causes damage and enormous losses of more and more valuable water. Therefore the Water Supply Company must invest more into maintenance and reconstruction of the system.

The Malenščica spring water is organically polluted due to its vast recharge area. It is also endangered by contamination because of rapid urbanization, industrialization and hazardous spills of dangerous substances. Considerable chemical contamination is due to unsuitable transport system, military training area and dumping in a direct recharge area. Water capacities of the spring are not yet completely exploited.

Introduction

Traditional water supply in the Pivka basin was organized in many different ways; by collecting rainwater (Phot. 1), digging wells, melting ice from the ice caves or melting snow in wintertime etc. But the easiest way was to use karst

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springs. They were not used only for drinking water supply, but their energy was also used for mill, blacksmith's workshop and sawmill driving. Where there was a lack of water it was necessary to provide it. To assure this precious liquid to the karst area in a sufficient quantity, first water reservoirs and water supplies were built.

Studied area, that is mainly connected to public water supply system, which pumps water from springs of the Malenščica stream, still has a huge reserve for supplying drinking water. But the population in Pivka basin constantly increases, causing needs for water supply from smaller karst springs or exploitation of groundwater near Zagorje. Water catchments from local sources that supply part of the population do not present reserves for drinking water supply, because they normally dry up in summer months. In the case of the Malenščica spring pollution, there would be no substitution source for the reliable water supply of the Pivka basin population, where more than 20.000 people live and work.

Phot. 1. Traditional drinking water supply by collecting rainwater (phot. N. Ravbar)

Objectives

Numerous abundant springs are typical of contact between karst and impermeable rocks. They are of great significance for drinking water supply for an extensive hinterland (for example the Hubelj, Malenščica, Rižana). So karst in many places and also in Slovenia is of vital economic importance. Almost half of the country is karstic and half of drinking water is obtained from karst aquifers.

Objectives of this contribution are to present historical development of drinking water supply and to show situation and water sources in the Pivka basin of today. Firstly the studied area and its historical background are represented. Description of present drinking water supply in the Pivka basin follows.

Final results about the drinking water exploitation in Pivka basin are presented: water resources, water supply extent and drinking water distribution, number of inhabitants, quantity and purpose of consumption data. I was also interested, from where the settlements that are not connected to public water supply get water. But I did not include a detailed record of local water supplies, which are maintained and managed by Local Communities.

As one of the aims of Water Frame Directive (WFD, 2000) is to promote manner of water exploitation, which protects available sources in long-term, I decided to find out actual situation in the field of drinking water supply in Pivka basin. Furthermore some suggestion for subsequent strategic water sources planning and management are proposed in addition to possibilities and limitations of the same.

Studied area

Karst plateaus surround Pivka basin. In the north steeply raises Nanos and Hrušica, in the east, southeast and south Javorniki and Snežnik, and in the west Slavenski ravnik, that descends into Košana valley.

Region is generally divided into Upper and Lower Pivka basin, where in the central part characteristics of karst and fluvial relief alternate due to different lithology of the basis. Upper Pivka basin, which stretches south of Prestranek, consists of limestone. In this part the Pivka river stream is seasonal, but floods during high water period. When the level of the underground water rises, shallow karst hollows are flooded and changed into seasonal karst lakes: Petelinjsko, Palško, Veliko and Malo Drskovško lake.

The bases of the Lower Pivka basin, which stretches north from Prestranek, is made of flysch and partly covered by river alluvium. Here branched surface flow prevails. The main river is Nanoščica, which is a tributary of the Pivka River.

Waters in this area flow into different directions. Where there is high groundwater level, it appears above the surface and fills up the riverbed of the Pivka River, which then continuously flows from Zagorje until it sinks into Postojnska jama cave. Smaller part of the Pivka River already disappears underground into small sinkholes in its riverbed, but mainly continues it's way towards Postojnska jama cave and flows underground into Planinsko polje. If the water level is low, underground waters flow under Javorniki Mountain towards Cerkniško polje. Javorniki Mountain constantly drains into springs of the Vipava and Timavo, however, smaller amounts also into springs of the Unica on Planinsko polje (Habe, 1963; Habič, 1989). Waters of the Lokva and Belščica streams that disappear near Predjama flow into spring of the Vipava (Michler, 1952; Habe, 1970).

Even though the riverbed of the Pivka River has already been regulated before the Second World War, at times floods still appear, preventing intensive cultivation. Agriculture is mainly self-providing, but the roll of stockbreeding is rising. In the region wood industry and poultry plants in Pivka are also important. Very successful are also metallurgy and electric industry. Pivka basin has extraordinarily important traffic role, because it lies in the road and railway crossroads of the European significance. Ravbarkomanda pass (612 m) is the lowest passage from the mainland to the closest Northern Adriatic ports that were used already in the Roman times. Road and railway links are drawn from the interior of Slovenia towards Slovenska Istra and Reka. However, towards Brkini only a road link is built. The city of Postojna itself grew up because of traffic, tourist and commercial favourable position.

Drinking water supply

Postojna and the settlements in its vicinity have been acquiring water from the springs under Nanos Mountain since 1929. It was connected into the Nanos-Postojna water supply system. The Malenščica spring exploitation of bigger extant goes back to the beginning of the past century, when in the times of Italian administration the inhabitants of Planina village have gained a local water supply. In 1972 both of the systems have been connected and enlarged. In the eighties building of the water supply system toward Pivka and surrounding villages was completed (Gospodarič, 1985, 1989).

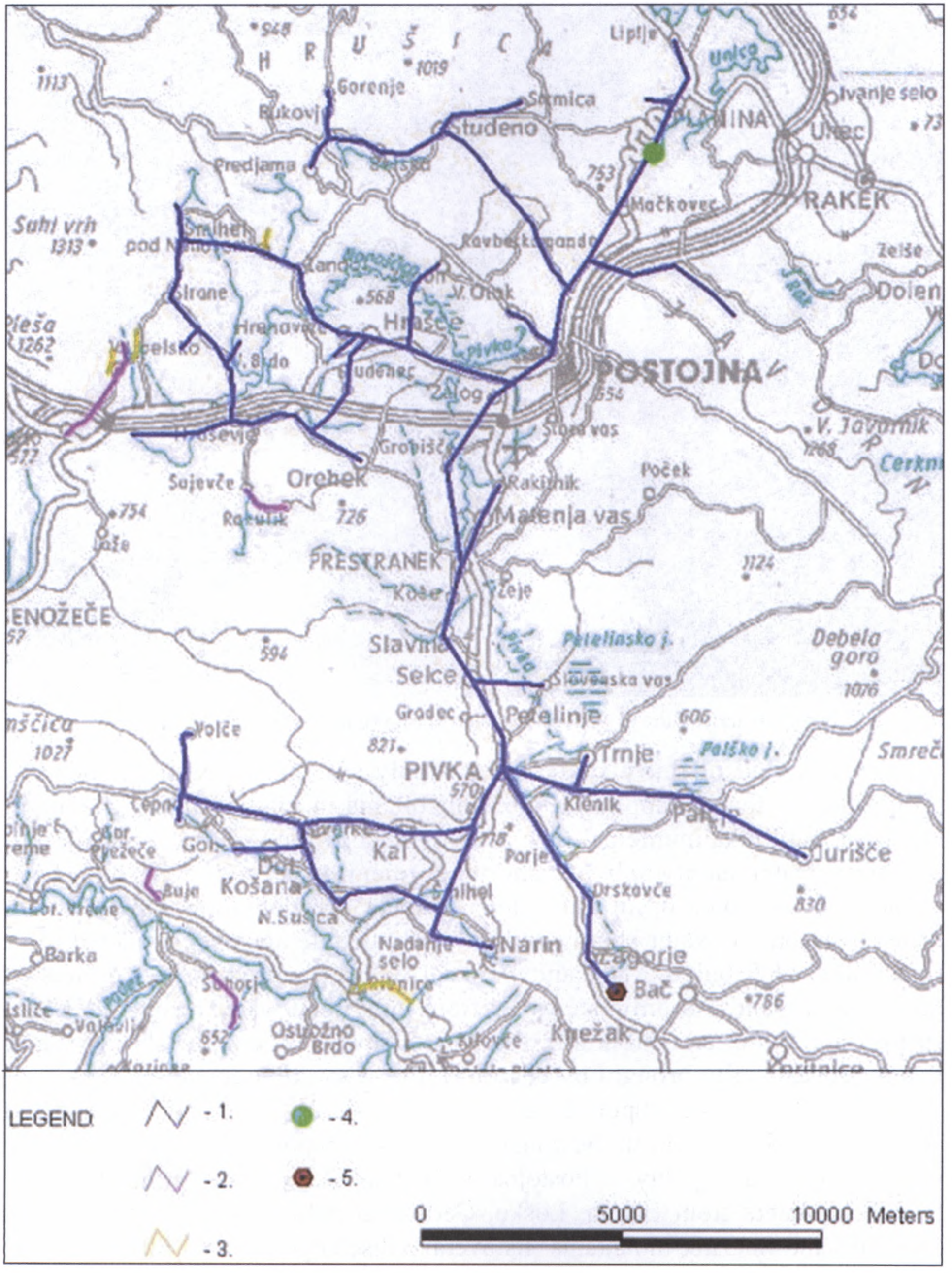

Fig. 1. Sketch of drinking water supply situation in Postojna and Pivka municipalities (based on GURS, TK 1 : 250.000)

1 – public water supply network, 2 – individual water resource, 3 – supply from local springs, 4 – the Malenščica river spring, 5 – connection to Knežak water supply

Phot. 2. Drinking water capture at Malenščica karst spring (photo N. Ravbar)

In the period of thirty years water supply system has been extended to such a degree that it supplies 19.862 inhabitants in totally 60 settlements in Postojna and Pivka municipalities; after the reconstruction and connection to the public water supply only few shorter segments of local systems have been abandoned. In Pivka basin there is 97 percent of population supplied with water from public water supply and only 590 people are not connected to it. Inhabitants of Ribnica, Malo and Veliko Ubeljsko and partly inhabitants of Šmihel pod Nanosom only use water from individual water resources. Local springs are exploited in Rakulik, Razdrto, Sajevče, Buje and Suhorje. Water is only occasionally brought by cistern (http://www.kovodpostojna.si).

The Postojna water supply system is 300 kilometres long and is considered as a medium size system in the country. The most important source of drinking water for the municipality of Postojna is the Malenščica karst spring (Phot. 2). It gathers waters from Babno, Loško, Cerkniško polje and Pivka basin, from Javorniki and Snežnik mountains. Its average discharge is about 10 $m^3 \cdot s^{-1}$ and minimum discharge reaches $1.3 m^3 \cdot s^{-1}$. The pumping station that on average pumps 0.085 $m^3 \cdot s^{-1}$ is located about 100 meters above the spring, so that it does not capture the main water stream. But its capacities are not yet completely used.

To Postojna water supply system are included also springs from under Nanos Mountain, contributing 0.005 $m^3 \cdot s^{-1}$ (10 percent), and boreholes near Zagorje. Smaller amount, not even one percent of water is contributed by local springs, which are not directly included in the central part of the water supply system (Fig. 1).

Water from the Malni springs is first pumped to the water treatment plant, which stands 70 meters above the spring and where the raw water is cleansed and sterilized. Afterwards water is pushed 165 meters higher and then gravitationally flows towards reservoirs above Postojna and above Pivka. To supply higher parts of Pivka, a part of water is again pumped to the 40 meters higher reservoir from where it flows towards Jurišče, Zagorje and settlements in Košana valley. In Zagorje water is again pumped in reservoir above the

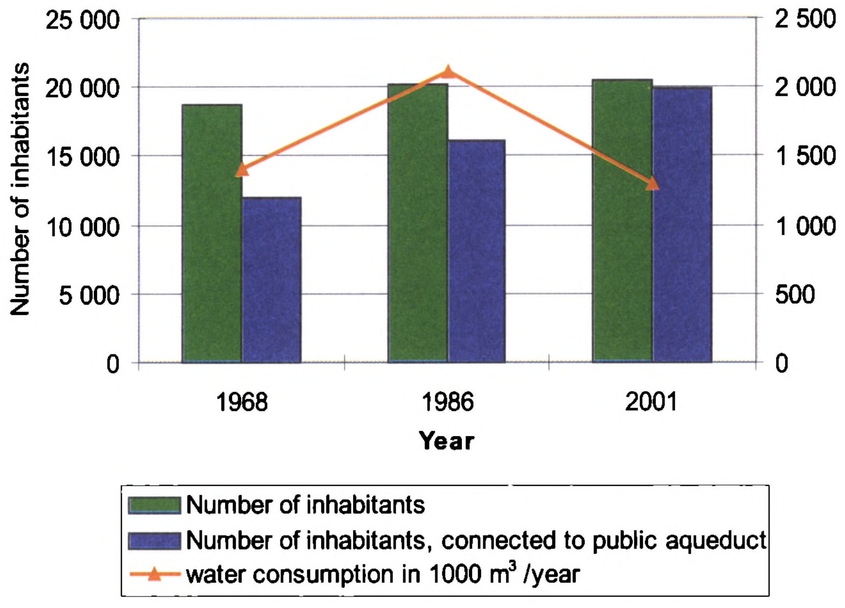

Fig. 2. Drinking water supply in Pivka basin in 1968, 1986 and 2001

village, allowing supply of the upper part of the village and at low water period an additional supply of the near water supply system Knežak–Bač–Koritnice in Ilirska Bistrica municipality.

In Postojna a part branches off the main one and supplies villages in Podgora and under Nanos Mountain. Separate branches in the system form a water supply for Hruševje with a reservoir of their own and Korotan water supply with the abandoned spring catchment. Central pipeline Postojna – Pivka is connected to

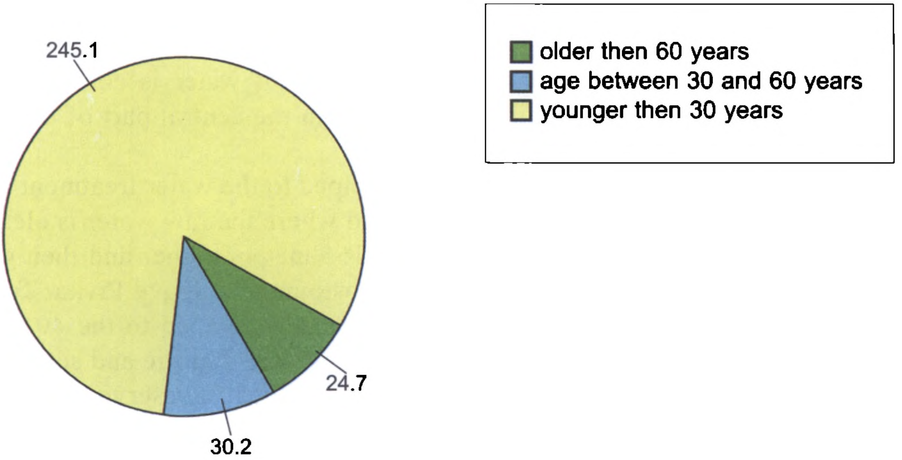

Fig. 3. Postojna water supply pipeline age structure (length of pipelines in km)

the water supply from springs under Nanos Mountain, which enables contemporary reciprocal feeding.

There are no exact data about drinking water use in Pivka basin in the past. P. Habič (1987) reports that in 1968 18.755 inhabitants lived there and that the annual consumption of water reached 1.4 million m^3. In 1986 number of population increased to 20.180 and consumption in the same year was 2.3 million m^3 (Habič, 1987). In the eighties consumption of water exceeded two million m^3 of water per year and heavily declined after the country reached independence. In the nineties consumption of annual amount of water came from 1.5 to 1.36 million m^3. This situation is due to great decline of the economic activity, which affected numerous firms and industry, large reduction of military discipline and consecutive a strong emigration. One of the basic reasons for decrease of drinking water consumption is certainly more and more rational behaviour of users.

In 2001 the amount of water, delivered into the system, was 2.7 million m^3, while the amount of sold water was 1.4 million m^3. Average use of water in Pivka basin is 114.000 m^3 of water per month. Average quantity of water in households is 820.000 m^3, in industry and firms 650.000 m^3 of water per year (Fig. 2). Among these the biggest users are poultry breeding and slaughterhouse Pivka in Neverke village, production of electrical household appliances, wheels, machine tools, lifting and transport gears LIV in Postojna and timber industry Javor in Pivka.

Water losses in the system are nearly 50 percent due to old network, bad quality of pipeline, lowering of the ground and other reasons. Almost one quarter of network is disused, because the infrastructure has not been renovated since its construction thirty years ago. In 1998 8.2 percent of the system was older than 60 years, 10 percent was between 30 and 60 years old and 82 percent of the system was younger than 30 years (Fig. 3).

Insignificant renovation of the old pipelines causes damage and a considerable quantity of water losses. Water Supply Company should therefore invest more into maintenance and renewal of the system. Further preventive measures for less wasteful management with drinking water would be use of water of bad quality for technological purpose and bigger consciousness of consumers (for example: problems in drinking water supply are caused by using water for washing the car, irrigating gardens during drought).

In the year of 2000 town councils of Postojna and Pivka municipalities have reached a decision about the restoration of the old water supply system Postojna – Pivka in order to reduce water losses. At the same time the installation of the water pipes to the villages with no water supply is undertaken as well. Connection to some remote dwellings in Postojna municipality is also planned until 2010 at the latest.

Difficulties in drinking water supply in studied area are not only in high losses in the system, but also in a serious ecological hazard of the existing water sources. Among these the most endangered is the Malenščica river spring. In its immediate vicinity pass the most important highway and railway. Water resources are constantly potentially endangered by noxious substances, which are being transported on the roads and railways among Unec, Postojna and Pivka. At an accidental spill the Malni water resource would become useless in few hours after and people of Pivka basin would be without drinking water.

The spring is also strongly endangered by Poček military training area on the Javorniki Mountain. Contamination of air and soil, where poisonous substances accumulate, and dumping, which is the consequence of military training, seriously pollute the Malenščica spring. Underground water tracing test showed that an important amount of water flowing into the spring comes from the military training area at Poček. In summertime rainwater needs two or three months to reach the spring, but constant and abundant rain would take only few hours to infiltrate through hundred meters thick limestone ceiling. It was proved, that apparent velocity of groundwater in the studied area is between 0.07 and 0.7 cm/s (Kogovšek et al., 1999).

In the doline in the spring's recharge area there is Postojna waste disposal site, where no collecting or treatment of dumping effluent exists. Water flows directly into karst, into drinking water storage. Problems of contamination are constantly growing because of increasing immigration, accelerated urbanization, transit transport of dangerous substances, industrial wastewaters and jumping growth of tourism (Kogovšek, 1996).

Water from the Malenščica spring is cleaned and sterilized with chlorine, before it is let into the system. The water is cleaned and prepared for drinking in the water treatment plant Malni near Planina. In case of a higher contamination of this water resource it would be necessary to abandon the catchment until pollution is completely removed; this could take many years. For the time being the inhabitants of the Pivka basin would lose the most important drinking water resource.

While planning drinking water supply in future it is advisable to include numerous local water sources in connection with traditional way of supply. Pressure on the existing water supply system would be smaller, if regional supply system is supplemented by smaller catchments. To make an attempt to revive local sources an eventual usage of rainwater or small springs for irrigation, washing cars, rinsing toilets or reusage of treated water for communal activities, such as washing the streets, for farming and as technological water in industry is not expelled. Measures for the less wasteful management of drinking water supply will also reduce exceeding and uneconomical quantity of the pumped water, which is also an objective of the National Environmental Action Programme 2001–2010 (http://www.sigov.si/mop/).

Minor pumping of drinking water could be achieved with effective improvement of water supply infrastructure in some parts of the system. In case of such quantity of losses as is found in Postojna water supply (about 50 percent), searching of new water resources is totally unnecessary.

Conclusions

Postojna water supply system supplies households and industry in Postojna and Pivka municipalities with drinking water. Its most important source is the Malenščica river spring. Some of water is also gained from karst springs under Nanos Mountain. Supply in the studied area is pretty settled and water is assured to numerous households even in remote parts. The water supply is connected to the one in Ilirska Bistrica municipality and occasionally supplies villages in this neighbouring municipality as well.

Depending on population and economy increase needs of drinking water supply constantly grow. Consequently it is necessary for the Postojna water supply to assure sufficient amount of quality water all over the year. Population and economy growth and numerous other socio-economic processes increase pressure on environment.

Karst aquifers in south-western Slovenia are due to natural properties very vulnerable. The most threatened are those that feed the most important water sources. But not enough attention is paid on conservation of water and its actual threat. Due to growing settlements in the karst area both in Slovenia and in the world it would be necessary to find out, to which degree groundwater could be pumped so that the equilibrium between exploitation and natural renovation is not ruined. Solutions, which would satisfy different needs of nature and modern society at the same time, have to be discovered.

Water of the Malenščica river spring is organically polluted due to its large recharge area. It is threatened by contamination because of rapid urbanization, industrialization and exposure to dangerous substances. Because of inappropriate transport system, military training area and dumping in the hinterland a danger of pollution is considerable.

Postojna water supply system depends on one important water resource only, which is a big disadvantage. In case of pollution the whole area could be left without drinking water or its quality can be limited and supply strongly interrupted. To assure disposal of unrestricted amount of quality water, it is advisable to use several different sources. This would enable vast distribution and prevent lack of water in dry period as well.

Area of dispersed small settlements, which is typical of the Pivka basin, demands branching and extensive network. Pumping and pushing of water demands too much energy consumption. Due to heavy losses in the system and renovation expenses the price of water additionally rises. Effort for water loss reduction in network needs to be supported.

While planning water supply in the studied area it would be convenient to include numerous local water sources in connection to traditional way of water supply. Water resources that have been abandoned in the past century could be refreshed, thus intensifying care for environment protection. Qualification and modernization of local water supply systems, wells and rainwater tanks could contribute to better quality and quantity of drinking water at the same time.

Economically more practical are therefore smaller catchments for individual settlement in connection to the central one. This would disburden large catchment and reduce risk of drinking water shortage. Nevertheless all the catchments must be connected in order to avoid inconvenience in water supply.

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Nataša Ravbar

Zaopatrzenie ludności w wodę pitną z zasobów wodnych w krasie (na przykladzie dorzecza Pivki, SW Slowenia)

Streszczenie

System wodociągowy Postojnej zapewnia zaopatrzenie w wodę pitną mieszkańcom i zakładom przemysłowym Postojnej i Pivki. Głównym źródłem zaopatrzenia tego systemu jest źródło rzeki Malenščica. Część wody pochodzi dodatkowo ze źródeł krasowych u podnóża góry Nanos. Jednym z podstawowych problemów funkcjonowania systemu zaopatrzenia w wodę w basenie rzeki Pivka jest zapewnienie odpowiedniej jakości wody oraz ograniczenie strat wody z sieci wodociągowej.

Niedostatecznie utrzymane stare rury wodociągów powodują częste awarie i w związku z tym coraz większe straty cennej wody pitnej. Przedsiębiorstwo wodociągów musi więc inwestować coraz większe środki w odbudowę systemu zaopatrzenia w wodę i jego konserwację.

Z uwagi na bardzo duży obszar zasilania wody źródła Malenščicy są zanieczyszczone związkami organicznymi. Jest ono również zagrożone w związku z szybką urbanizacją, industrializacją i niebezpiecznymi wyciekami groźnych substancji. Znaczące zanieczyszczenie chemiczne jest wynikiem niewłaściwego systemu transportowego, lokalizacji wysypisk śmieci oraz usytuowania poligonu wojskowego w bezpośredniej strefie zasilania źródła. Zasobność źródeł nie jest aktualnie w pełni wykorzystana.

Nataša Ravbar

L'alimentation de la population en eau potable des ressources souterraines dans la région karstique (à l'exemple du bassin de Pivka, SW Slovénie)

Résumé

Le système de conduite d'eau à Postojna assure l'alimentation en eau potable de la population et de l'industrie de Postojna et Pivka. La source principale de ce système est la source du fleuve Malenščica. Une partie d'eau provient en plus des sources karstiques au pied de la montagne Nanos. Un des plus importants problèmes du fonctionnement de système de conduite dans le bassin du fleuve Pivka est la garantie de la quantité suffisante et la limitation des pertes d'eau du réseau de canalisation.

De vieux tuyaux insuffisamment renouvelés provoquent de nombreuses détériorations et des pertes d'eau potable de plus en plus importantes; par conséquent la Régie Municipale des eaux doit investir des fonds considérables en la conservation et réparation du système.

A cause d'une grande surface d'alimentation en eau, la source de Malenščica est infectée par des matières organiques. En plus, elle est menacée par une forte urbanisation et une industrialisation et des fuites des substances dangereuses. Une pollution chimique grave est l'effet d'un mauvais système du transport, d'une localisation des décharges publiques et d'un polygone militaire dans le voisinage de la zone d'alimentation directe. Les ressources potentielles de la source ne sont pas actuellement mises à profit.

First received: December 2003.

„Kras i Speleologia". T. 12 (XXI). Katowice 2008
Prace Naukowe Uniwersytetu Śląskiego nr 2537

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The valuation of the Triassic major aquifers of the Upper Silesian Region

Abstract: The valuation procedure of the fissured – karst Triassic aquifers presented in this paper follows the basic and supplementary criteria. The basic criteria are water quality and vulnerability of a groundwater system. As the supplementary criteria it has been included: the state of reserves of groundwater resources, the importance of groundwater system in water supply expressed by the pumpage rate of water, the importance of the aquifer in regional water supply system and the recharge rate of aquifer.

Introduction

The Triassic aquifers are located within the Upper Silesia urban-industrial region. This region constitutes one of the most industrial area in Europe. It is caused by huge concentration of deposits: hard coal, zinc and lead ores and other raw materials. In total all 56 mining areas together with hard coal mines have a total area reaching 1750 km^2. The population is about 3 908,000 inhabitants within the area of ca 6650 km^2. Anthropogenic pollution sources exert the most effective threat to groundwater. Their maximum concentration occurs in the central part of the Silesian Industrial District. Mining activity is the factor that leads to large-scale qualitative and quantitative changes in water environment. Groundwater of the region is the second in magnitude source of water. Its contribution is about 30%. Potable groundwater in this area occurs within the

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Quaternary, Tertiary, Cretaceous, Jurassic, Triassic, Carboniferous and Devonian formations. The most valuable are fissured – karst Triassic aquifers. Above 50% of total groundwater resources is attributed to these aquifers. Triassic aquifers are drained by well fields and by mines. Due to the variability of hydrogeological conditions (quantity and quality of groundwater resources), possibilities of usage and because of management planning reasons the valuation of groundwater of the Triassic aquifers has been performed.

At the first stage 5 major Triassic aquifers have been identified within the research area applying generally accepted hydrogeological criteria (Różkowski et al., eds., 1997b). Next, the valuation of these aquifers has been done applying several quantitative and qualitative criteria (Witkowski et al., 1998). It enables to distinguish aquifers of fundamental importance for water supply and for management planning.

Hydrogeological characteristics of the Triassic fractured-karstic aquifers

The Paleozoic formations of the variable age are the basement of the Triassic formation of the Silesia–Cracow Monocline. The geological profile of the Triassic consists of sandy-silty and carbonate sediments of the Lower Triassic, carbonate sediments of the Middle Triassic and clayey sediments of the Upper Triassic. The Triassic formation is locally covered by the Jurassic carbonate and clayey sediments and the Tertiary clayey formation. The Quaternary formation of variable thickness (from less than 1m to tens of meters) covers all area. The Quaternary deposits are represented by sands, clays and silts.

The area of the Silesia–Cracow Monocline is characterised with block tectonics. The rock massif is strongly cracked and fractured. The Muschelkalk and Rhaetian carbonate rocks have undergone multi-stage karstic processes.

The research done by J. Motyka and the others (1996), carried mainly in the Olkusz, Pomorzany and Trzebionka Zn-Pb ore mines, has shown significant cavernity of the rocks belonging to the Triassic carbonate series, causing the high permeability of the rock massif. These researchers have indicated that rock cavities were formed mainly as a result of the corrosive water action as well as in the process of the mechanical rock destruction. The presence of cavities, left in old mine workings, is also observed in the Tarnowskie Góry, Bytom, Olkusz, Chrzanów areas being the fields of the old Zn-Pb ore exploitation.

The Muschelkalk and Rhaetian aquifers occurring in the hydrogeological profile of the Middle and the Lower Triassic formation are built mainly of limestones and dolomites. They are fractured-karstic aquifers (Różkowski, ed., 1990; Różkowski at al., eds., 1997b). The layer, separating the mentioned aquifers, is composed of marl-clayey laminae present in the Gogolin strata. As a result of tectonic and sedimentary conditions and geochemical alteration the Gogolin strata may lost their insulating properties. Moreover, recently the Muschelkalk and Rhaetian aquifers are more often jointly exploited as one water-bearing complex (Różkowski, ed., 1990). The thickness of the water-bearing formation of the Triassic carbonate series is in the range of 20–160 m. The depth interval of water-bearing complex occurence is in the range of 100–400 m. Due to the various thickness and high heterogeneity of the rock medium the transmissivity of this complex is variable spatially in the range from a few up to about 80 m^2/h. The specific discharge of a well is variable in the range of 1.0 to 535 m^3/h, with tendency to its decrease with depth.

Within the Triassic formation the major aquifers have been identified with very advantageous hydrogeologic conditions. They were determined on the basis of the following quantitative and qualitative criteria proposed in the Kleczkowski's work (ed., 1990):

- transmissivity of aquifer – over 10 m^2h^{-1},
- potential yield of an individual well – over 70 m^3h^{-1},
- total capacity of a well field – over 10 000 m^3 per day,
- water quality – equivalent to I, II and III quality classes (according to classification proposed by the State Inspection of Environmental Protection), and IV class – out of classification.

According to the nomenclature and numeration applied in Kleczkowski's work (ed., 1990) the Gliwice 330, Myszków-327, Bytom-329, Olkusz–Zawiercie-454 and Chrzanów-452 aquifers belong to the major aquifers (MAs) (Fig. 1). They are karstic aquifers, often partially hydrogeologically covered, relatively low "sensitive" to the recharge impulse. Under conditions of mining exploitation and under the influence of intensive deep drainage, the reaction to the intense raining is shorter.

The Triassic aquifers are the main source of usable groundwater supply for the urban-industrial agglomeration of the Upper Silesia region. The Gliwice, Lubliniec–Myszków, Olkusz–Zawiercie–Chrzanów MAs are partially protected by clayey Rhaetian-Keuper rocks and locally by clayey Quaternary sediments. The thickness of these, practically impermeable formations reaches up to about 300 m. The MAs are hydrodynamically confined or partly confined. The intensive groundwater drainage by mining and well fields has caused changes in hydrodynamic conditions. It concerns the mine workings of Zn-Pb ore mines in the Bytom, Olkusz and Trzebinia areas and well intakes in the Bibiela, Łazy Błędowskie and Gliwice areas (Fig. 1). As a result of overexploitation of some MAs vast cones of depression have been formed. Regional decline of pressure, up to 200 m in the mining drainage areas, and flow pathways inversion have been found. In the recharge areas the groundwater level is at the depth of 10–50 m under surface level (Różkowski et al., eds., 1997b).

The aquifers are recharged in the outcrops of the Triassic carbonate series by permeable and semi-permeable Quaternary formations. The thickness of

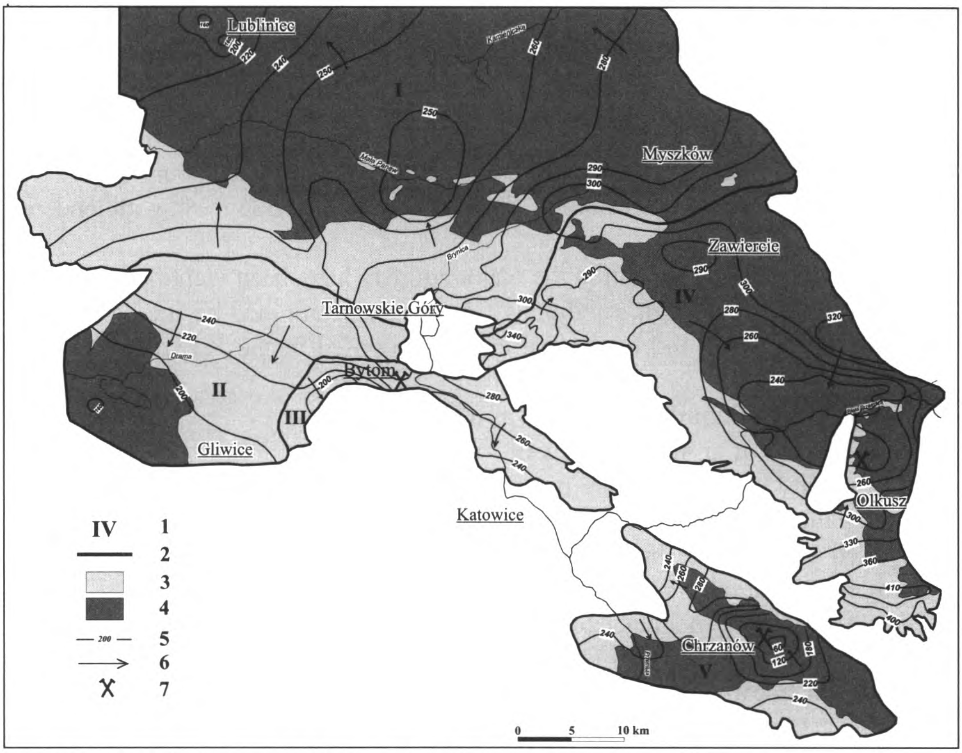

Fig. 1. Hydrogeological map of the Triassic Silesia–Cracow major aquifers

1 – Triassic major aquifers (TMA): I – Lubliniec–Myszków, II – Gliwice, III – Bytom, IV Olkusz–Zawiercie, V – Chrzanów; 2 – TMA borders; 3 – the outcrop areas of the Triassic carbonate series (recharge areas); 4 – the areas of the covering of the Triassic carbonate series by isolating formations; 5 – hydroisohips of the Triassic carbonate complex; 6 – groundwater flow directions; 7 – Zn-Pb ore mines

the Quaternary deposits is various in the range of less than 1m up to tens of meters. The additional source of recharge are water-courses infiltrating into the ground. Also the forced lateral and ascensional recharge, both in the case of geologically older as well as younger water-bearing horizons in the areas of the active drainage, is observed (Kowalczyk et al., 1996; Motyka, 1988; Różkowski et al., eds., 1997b).

In the past, the drainage zones of the water-bearing complex of the Triassic carbonate series were the modern and buried river valleys. Recently this role has been taken by the main areas of concentrated anthropogenic drainage.

Dolomite-limestone hydrogeological environment of the Triassic MAs is heterogeneous, discontinuous and anisotropic. Anisotropy of the rock massif is related to the joint and stratification fissures and karstic cavities.

Hydraulic structure of rock environment of the Triassic carbonate series consists of three hydraulic systems in respect to geometry and size: porous, fractured and karstic ones. They are characterized by transmissivity and hydraulic capacity of the rock massif and their measure are the values of hydraulic conductivity, effective porosity and gravity drainage capacity.

Characteristic values of the hydraulic conductivity for the phreatic zone of the fractured-karstic water bearing complex of the Triassic Silesia–Cracow carbonate series are variable in the range 10^{-6}–10^{-3} m/s (Różkowski, ed., 1990; Różkowski et al., eds., 1997b). The high values, occurring mainly in the outcrop zones of the Triassic carbonate series, are characteristic for strongly fissured and cavernous rock massif while the low ones for the rock massif with low fissility and with karstic forms infilled by sediments of low permeability. The research, led in the area of the Lubliniec–Myszków MA in the 60-450m depth interval, has indicated decrease of their values with depth from 1.6×10^{-4} to 2.0×10^{-6} m/s (Różkowski, ed. 1990).

In the vadose zone, in the range of the weathering fissure occurrence in the areas of mining activity the hydraulic conductivity of the carbonate rocks is very high, in the range of 10^{-3}–10^{-0} m/s.

Hydraulic structure of the analyzed rock massif is dynamic and variable in time as a result of influence of the geogenic and anthropogenic factors. Among the latter, the particular significance seems to have exploitation of the Zn-Pb ores present in the Muschelkalk formation, lasted in this region since the Middle Ages. Mining exploitation and active drainage have caused the additional rock massif cavernity and the exhumation of the old karstic system infillings.

Various values of hydraulic conductivity in particular hydraulic systems of the Triassic carbonate massif cause different water flow rate. In the channel systems the flow rate values are in the range of tens of thousands m/y, whereas in the fissure systems from tens of hundreds to several thousands m/y (Motyka, 1988). The average flow rate through cracked and cavernous carbonate rock massif, considering its matrix porosity, is in the range from tens to tens of hundreds m/y, reaching in the area of the active anthropogenic drainage the values of about 2 thousands m/y (Różkowski, ed., 1990).

Groundwater drainage by mining and well fields has caused significant changes in rates of recharge and discharge, and finally in groundwater resources. It concerns the Triassic aquifers drained by Zn-Pb ore mines, partly by coal mines too (Kowalczyk et al., 1999). Estimated groundwater resources of Triassic aquifers vary from about 2 Mm^3/year to 168 Mm^3/year (Table 1) (Różkowski et al., eds., 1997b). The recharge ratio varies from 107 $m^3/d \times km^2$ to 553 $m^3/d \times km^2$. The highest recharge rate values are induced by intensive drainage of groundwater in some mining areas.

The development degree of the resources is various (Table 1). The total pumpage of groundwater from the major aquifers is about 385 Mm^3/year.

Table 1

Groundwater resources of major aquifers, their quality and vulnerability

No	No of aquifer according to Kleczkowski, (ed., 1990)	Strati-graphy	Area [km^2]	Groundwater Resources [Mm^3/year]	Recharge rate [$m^3/d \times km^2$]	Pumpage [Mm^3/year]	Ground-water Quality Classes	Thickness of isolation cover or depth to aquifer [m]	Vulnerability
1	327	T	557	31.6	107	42	II,III,IV,Ib	50–250	moderate
2	330	T	411	45.1	298	29	Ib,II,III	50–150	moderate
3	329	T	130	26.4	553	26	II,III,IV,Ib	50–150	moderate
4	454	T	1033	168.36	449	150	Ib,II,III,IV	50–150	moderate
5	452	T	247	29.69	369	27	II,Ib,IV,III	50–150	moderate

Groundwater chemistry and quality

Considerable differentiation characterises chemical composition of waters in the Triassic carbonate series of the major aquifers: Lubliniec–Myszków, Gliwice, Bytom, Olkusz, and Chrzanów. Waters of investigated populations are representative for fresh waters, acratopegae, and mineral waters as well. Mineralization of water, expressed as dry residue, ranges from 103 mg/L to 1519 mg/L. Its representative values are those in the limits of 104 mg/L and 480 mg/L. Waters are classified among HCO_3–Ca–Mg and HCO_3–SO_4–Ca–Mg hydrochemical types. In the event of serious deterioration of their quality, they become poly-ionic (locally only).

Transformation of natural chemical composition of groundwater in the Triassic major aquifers due to anthropogenic and geogenic factors has caused changes in the quality of this water. A short time, usually less than 25 years, of a vertical infiltration of water in the recharge areas of the major aquifers favours the intensive degradation of groundwater (Różkowski et al., eds., 1997b).

Generally two groups of water quality were specified in the Triassic major aquifers: suitable for drinking water supply (Ia, Ib, II, III classes), and unsuitable for drinking water supply (IV class) (Table 1).

In a quality ranking, groundwater of the Lubliniec–Myszków major aquifer belongs to Ib, II, III classes, in small amount to IV class. Water of Ia class has not been recorded. Among all hydrochemical elements determining the water quality, the concentration of strontium, iron, barium, sulphate and nitrate have been recorded to exceed the normative values.

In Gliwice major aquifer, slightly degraded and degraded water predominate; this belongs to Ib and II classes. Also water of high quality degradation which belongs to III class occurs. Increased concentrations of Ba^{2+}, Sr^{2+}, SO_4^{2-}, NO_3^-, Mn^{2+} and Al^{3+} determine the attachment to these classes.

In the Bytom major aquifer low quality water (classes II and III) and intensively degraded water (IV class) occurs. It is related to the increased concentration of NO_3^-, SO_4^{2-}, Cl^-, Na^+, Ba^{2+}, Mg^{2+}, NH_4^+ and hardness.

In the Olkusz–Zawiercie major aquifer high quality water (Ib class) predominates. Also slightly degraded water of medium and low quality occurs; this belongs to II and III classes. Locally, unsuitable for drinking purposes water, of the IV class occurs. Degradation of water is manifested by increased concentrations of SO_4^{2-}, Fe_{total}, Mn^{2+}, NH_4^+, Pb^{2+}, Cu^{2+} and Cd^{2+}. A characteristic feature of this major aquifer is that groundwater is locally polluted by lignosulfonates.

In the Chrzanów major aquifer, high quality water (Ib class) predominates. However, degraded water was recorded in the areas of urban–industrial agglomeration.

Essential influence is observed of extraction of Zn–Pb ore deposits upon chemical composition and quality of water in the Muschelkalk aquifer. Poor quality waters (classes II and III) occur within mining areas; this fact is connected with increased values of dry residue, hardness, and concentrations of SO_4^{2-}, Cl^-, Na^+, K^+, NO_3^-, NH_4^+, Fe_{total}, Mn^{2+}, Zn^{2+}, Pb^{2+}, Ba^{2+} and Sr^{2+}. If dry residue, hardness, and concentrations of SO_4^{2-}, Cl^-, NO_3^-, Fe_{total}, Pb^{2+}, Zn^{2+}, and Sr^{2+} are high, then waters are being classified among excessively polluted (class IV).

Vulnerability of the Triassic major aquifers

Vulnerability assessment of groundwater was based on the travel time of water nad pollution from the surface to an aquifer. This time and its variability depends on thickness of isolation cover overlying the aquifer or the depth to the unconfined aquifer (Paczyński, 1997).

Vulnerability assessment is performed according to the following main criteria presented in the Table 2:

– high – travel time up to 25 years, weak isolation up to 50 m thick,
– moderate – travel time 25–100 years, isolation cover 50–150 m thick,
– low – travel time more than 100 years, isolation cover more than 150 m thick.

Groundwater vulnerability to the surface contamination evaluated by the presented criteria has been confronted with calculated values of the residence time of groundwater in aquifers as well as the reaction of springs and wells and mine inflows on the impulse of the precipitation and snowmelting (Kowalczyk et al., 1999).

The fractured-karstic Triassic MAs: Lubliniec–Myszków (327), Gliwice (330), Bytom (329), Olkusz–Zawiercie (454) and Chrzanów (452) are characterized by very various vulnerability, both within the basins range, as well as between them (Fig. 1).

The Lubliniec–Myszków aquifer is naturally protected on about 75% of its area by the clayey Rhaetian–Keuper sediments covering it. The results of isotope analysis (^{14}C, T, ^{18}O, D) have indicated that below the impermeable covering of the Upper Triassic formation residence time of groundwater is variable in the range from tens of hundreds to tens of thousand years (Różkowski, 1993), indicating almost total lack of vulnerability to anthropogenic pollution in this part of the aquifer. High vulnerability has been shown by the outcrop area, extending parallel to the latitude in the southern part of the aquifer (Fig. 1). The time of the vertical seepage varies here in the zone of uncovered outcrops from less than 1 year and up to 24 years under the cover of permeable and semi-permeable Quaternary formations. These figures are confirmed by the results of quantitative analysis of tritium content in groundwater. The very low values of time of the vertical seepage, occurring locally in the zones of the Triassic carbonate formation outcrops, and the same, very high risk degrees have been confirmed by the piezometric observation of the reaction of water horizons to recharge.

The Gliwice MA groundwater vulnerability to anthropogenic pollution from the ground surface is various depend on the aquifer isolation degree. Calculated by J. Kropka (Różkowski at al., eds., 1997a) values of time of the vertical seepage of groundwater through the vadose zone 10–76 m thick, are very variable and are in the range from 2.5 to more than 260 years. High time of the vertical seepage is characteristic for the aquifer parts covered by the clayey Tertiary formations. Calculations have not shown the values of time of the vertical seepage through the vadose zone lower than 2 years, what, according to the mentioned author can be related to significant lowering of the groundwater table as a result of intensive drainage. The results of tritium content in groundwater have indicated the age being in the range from a few up to several years.

A. Kowalczyk and A. Idziak (1996), analysing the hydrogeological conditions of the Staszic intake in Tarnowskie Góry region, have shown that its maximum reaction time to rain recharge is several months. These data indicate that in the areas of the carbonate series rock massif drainage, caused by old mining, vulnerability of the Triassic water-bearing complex is high and differs from that calculated by classical empirical formulae. This area is a region of high pollution risk to groundwater.

Valuation of the Bytom MA vulnerability to anthropogenic pollution is exceptionally difficult and can be incorrect. This is related to complicated hydrogeological conditions resulting from mining exploitation of Zn-Pb ore mines and coal mines (Kropka, 1996). Long-term ore exploitation has caused higher permeability of rocks and drainage of the Muschelkalk aquifer. Long wall exploitation of coal seams has led to deformation of the Triassic rock massif. As a result theoretically calculated time of the vertical seepage through the vadose zone is overestimated. The J. Kropka's observations (personal information) have indicated that after the violent rains in 1997, the groundwater inflows to mine workings of the abandoned Orzeł Biały ore mine, increased in 50%, were observed just after a few weeks. Research of J. Kropka concerning west and east parts of the Bytom MA, situated beyond the range of the mining drainage, has shown a variable degree of the natural isolation of the carbonate water-bearing complex. In the western part of the aquifer the cover, composed of the Quaternary tills and the Tertiary clayey patches, are present in its roof. Vulnerability of the Triassic aquifer is low here and reaches 25 years. It is the region of low risk to the groundwater environment. However, in the eastern part of the aquifer its vulnerability is high, what is shown by values of time of the vertical seepage being in the range from a few up to several years. This aquifer part could be included to the areas of high and medium environmental risk.

The Triassic Zawiercie–Olkusz MA vulnerability is various. In the northern and north-eastern part it is practically not threated by potential pollutants. It is due to its natural isolation by the clayey Rhaetian–Keuper sediments covering it. The aquifer is very low vulnerable. The theoretical values of time of the vertical seepage are more than 100 years. Generally, the area with low vulnerability and low or very low risk degree includes about 62% of the aquifer area. However, in the range isolating Rhaetian-Keuper formation occurrence found in the roof of carbonate series, highly vulnerable to surface anthropogenic pollution are areas in the Przemsza buried river valley near the Olkusz and Łazy Błędowskie towns. The southern and western parts of the aquifer, situated in the range of the recharge area of the water-bearing complex of the Triassic carbonate series is characterized by high vulnerability to anthropogenic pollution. The values of time of the vertical seepage are in the range from 1 to several years, indicating high risk to the water environment. The short times of vertical seepage are confirmed by tritium content in groundwater. Observations of the time reaction of the springs to atmospheric precipitation, led in Góra Siewierska region in the area of outcrops of the carbonate series, have revealed the short time of water circulation, within the several months range (Kowalczyk, Witkowski, 1997).

The rock massif in the Olkusz mining area is actively drained and highly permeable due to mining exploitation, led here since the Middle Ages. This part of the MA is particularly vulnerable. The values of vertical seepage time calculated for this area with the use of empirical formula are in the range of less than 1 year to several years.

The Chrzanów Triassic MA is naturally protected by the isolating Rhaetian–Keuper and locally the Tertiary formations in the 60% of its occurrence area. The aquifer is low vulnerable in these areas. The values of vertical seepage time through the vadose zone are in the range a few tens years or even more than 100 years. The rest of the aquifer, consisting of about 40% of its area, is uncovered from the hydrogeological point of view. The values of vertical seepage time is variable, depending on thickness and lithological structure of the covering Quaternary deposits. The calculated values of point vertical seepage time are in the range from less than 1 year to a few years. This fact has been confirmed by the isotopic analysis of groundwater from the carbonate series investigated in the outcrop zone. Considering the values of point vertical seepage time through the vadose zone, these areas should be included into high and very high environmentally threatened.

The active drainage up to 200 m deep and the increase of the rock massif permeability due to Trzebionka mine activity in the south-eastern part of the MA have caused the increase of the vertical and horizontal flow to the high real values. Due to high flow velocity in the fractured-karstic rock massif, the surface anthropogenic pollutions can be transported to large depths in relatively short time.

Groundwater valuation

There are serious differences between the principles of groundwater valuation aimed at identifying the groundwater systems, which are most valuable for the society. The groundwater is valued mainly in economic terms (Custodio, Gurgui, eds., 1989; Winpenny, 1996). In the past hydrogeologic assessment has been mainly limited to the evaluation of groundwater resources and quality of water. Recently the method of valuation of groundwater by assessment of its vulnerability to pollution as an important criterion have been developed (Albinet, Margat, 1970; Vrba, Zaporożec, eds., 1994; Cost action 65, 1995; Eaton, Zaporożec, 1997; Vrba, Zaporożec, 1999). However there are important differences between the principles of the proposed methodology of valuation. For example, the valuation method proposed by Scharp et al. (1997) recognises such criteria as: available quantities of groundwater, groundwater quality, present or planned use and sensitivity to changes in groundwater level. It does not take into account such important criterion as vulnerability of the groundwater.

Concept and criteria of valuation

The valuation presented in this paper was performed according to the assumption and methodology proposed by Paczyński (1995, 1997) modified by the authors (Kowalczyk et al., 1998; Witkowski et al., 1998). The valuation procedure follows the basic criteria (Tab. 2) and supplementary criteria (Table 3). The basic criteria are water quality and vulnerability of a groundwater system.

As the supplementary criteria it has been included: the state of reserves of groundwater resources α, the importance of groundwater system in water supply expressed by the pumpage rate of water from an aquifer β, the importance of the aquifer in regional water supply system γ and recharge rate of aquifer system δ expressed in $m^3/day \cdot km^2$. The higher value of the recharge rate the lower numerical index δ. The list of applied criteria and their numerical indices used for valuation of aquifers is shown in Table 3 and 4.

Table 2

Basic valuation criteria (*w*)

Groundwater quality	Vulnerability as function of isolation cover or depth to aquifer		
	low > 150 m	moderate 150–50 m	high <50 m
Very good	10	7	5
Good	8	5	3
Moderate	6	3	1
Poor	0.5	0.5	0.5

The value of the groundwater *W* has been found as produce of basic valuation criteria index (*w*) compiled in Table 4, then multiplied by indices corresponding to supplementary criteria, summarised in Table 4. The final result of valuation is described by the equation (1):

$$W = w \cdot \alpha \cdot \beta \cdot \gamma \cdot \delta \qquad (1)$$

(explanations of symbols are given in the text).

Table 3

Supplementary criteria of valuation: α, β, γ, δ

Criteria	Valuation parameter	Index
α – reserves of groundwater resources	< 25% of max 25–50% of max >50% of max	1.5 1.25 1.0
β – pumpage	<1 Mm^3/year 1–10 Mm^3/year >10 Mm^3/year	1.0 1.25 1.5
γ – importance of the aquifer in water supply	the main or the only source of water-alternative source	1.5 1.0
δ – recharge rate of aquifer	100–300 m^3/day km^2 300–500 m^3/day km^2 >500 m^3/day km^2	1.5 1.25 1.0

Results

Results of valuation of aquifers are presented in Table 4. The aquifers have been included into four classes of value on the basis of performed valuation:
>15 points – extremely high (A),
10–15 points – high (B),
5–10 points – moderate (C),
< 5 points – low (D).

Table 4

Results of valuation of major aquifers

No	No of aquifer according to Kleczkowski, (ed., 1990)	Stratigraphy	Criteria of valuation					Value of aquifer	
			w	*α*	*β*	*γ*	*δ*	points, *W*	class
1	327	T	5	1.5	1.5	1.5	1.5	25.3	A
2	330	T	4	1.5	1.5	1.5	1.25	16.9	A
3	329	T	2	1.5	1.5	1.5	1.25	4.5	D
4	454	T	4	1.5	1.5	1.0	1.0	16.9	A
5	452	T	3	1.5	1.5	1.5	1.25	12.6	B

It has been found that one aquifer presents low value (class D). Its groundwater is vulnerable to pollution and it is polluted in the different degree. Three Triassic aquifers show extremely and one high value (classes A and B). The high rank of these aquifers is confirmed by quantity and quality of their groundwater resources and their importance in water supply.

All analysed major aquifers are of importance in water supply of the region. However, the aquifers classified as belonging to A and B classes are of the highest rank and their exploitation has to be limited to the supplying in drinking water. The special protection of water quality in these aquifers is also required.

Conclusions

For the Upper Silesia region 5 major productive aquifers has been identified, based on some hydrogeologic criteria. These aquifers are of different importance for groundwater supply and for management planning.

With respect to valuation assessment the aquifers of high value, class A and B, should be subject to special protection and groundwater exploitation should be strictly controlled.

The Triassic aquifers are the most important aquifers in terms of the usable water supply of the Upper Silesia region. Some of them have been too intensively and not rationally exploited by water intakes and they have been drained by mine workings. For these aquifers a new program of a rational exploitation and groundwater protection should be done. Particularly the proper localization of wells, restriction of exploitation for industry purposes and rational control of groundwater withdrawal is vital. Closure of some wells is advisable too. The protection areas of discussed aquifers drawn on the maps in the scale of 1 : 50.000 should be legally valid. In this new version of the protected areas there should be taken into consideration the latest state of hydrogeologic knowledge of aquifers, their resistance to anthropogenic pollution as well as areal distribution of national parks, landscape parks and areas of protected landscape. All activities that represent a threat to the groundwater should be banned from these areas either because of the groundwater vulnerability or because of the value of the groundwater.

The methodology of valuation presented in the paper give the priority to quality of water and vulnerability of aquifers. These criteria seem to be the most important in the valuation procedure of aquifers with very differentiated hydrogeologic conditions. The additional criteria are depended on regional conditions. For example sometimes it is not possible to take into account an alternative source of ground- or surface-water.

Although methodological unification of groundwater valuation is not purposeful and possible, the method of valuation should be developed. It enables identification of the most valuable aquifers. It is also a valuable guide for planners and decision makers for improving the rational water management and the protection of the groundwater resources at regional level.

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Andrzej Różkowski, Andrzej Kowalczyk, Andrzej Witkowski

Waloryzacja głównych zbiorników wód podziemnych serii węglanowej triasu regionu Górnego Śląska

Streszczenie

W niniejszym artykule podano propozycje waloryzacji pięciu głównych zbiorników wód podziemnych serii węglanowej triasu, zlokalizowanych w regionie Górnego Śląska (Gliwice – GZWP 330, Lubliniec–Myszków – GZWP 327, Bytom – GZWP 329, Chrzanów – GZWP 452 i Olkusz–Zawiercie – GZWP 454). Podczas waloryzacji zbiorników zastosowano metodę punktową na podstawie tzw. kryteriów głównych i uzupełniających. Do kryteriów głównych zaliczono jakość wód oraz podatność wód podziemnych na zanieczyszczenie (stopień izolacji zbiorników). Kryteria uzupełniające stanowiły: deficytowość zbiornika wyrażona stanem rezerw zasobów dyspozycyjnych, rola wód podziemnych w zaopatrzeniu, wyrażona wielkością poboru oraz wyróżnieniem zbiorników będących jedynym lub głównym źródłem zaopatrzenia w wodę, wskaźnik zasobności wyrażony w postaci modułu zasobów odnawialnych. Ostateczną wartość danego zbiornika (W) uzyskano przez przemnożenie indeksu w, otrzymanego na podstawie kryteriów głównych, przez 4 indeksy (α, β, γ, δ) wynikające z kryteriów uzupełniających. Zastosowano czterostopniową klasyfikację waloryzacji zbiorników: A – bardzo duża wartość zbiornika ($W > 15$), B – duża wartość ($W = 10–15$), C – średnia wartość ($W = 5–10$) i D – mała wartość ($W < 5$). Według wymienionych kryteriów za zbiorniki o bardzo dużej wartości uznano: GZWP 327, 330 i 454, przy czym największą ilość punktów kwalifikacyjnych (indeks W) uzyskał zbiornik Lubliniec–Myszków (GZWP 327). Spośród analizowanych pięciu zbiorników najmniejszą wartość ma zbiornik Bytom (GZWP 329). Biorąc pod uwagę wyniki wykonanej waloryzacji należy stwierdzić, że najbardziej wartościowe zbiorniki (klasy A i B) powinny podlegać specjalnej ochronie, a pobór z nich wody powinien być ściśle kontrolowany. Prezentowana metoda waloryzacji GZWP ma charakter szacunkowy, wynikający głównie z przyjętych do obliczeń uśrednionych

wartości wskaźników przeliczeniowych, i należy ją nadal rozwijać. Identyfikacja najbardziej wartościowych zbiorników wód podziemnych powinna być bardzo ważnym elementem branym pod uwagę w prawidłowej gospodarce wodnej i efektywniejszej ochronie zasobów wód podziemnych w skali regionalnej.

Andrzej Różkowski, Andrzej Kowalczyk, Andrzej Witkowski

La valorisation des réservoirs principaux d'eaux souterraines de la série carbonate du trias de la région de Haute Silésie

Résumé

Dans l'article nous avons présenté des propositions de la valorisation de cinq réservoirs principaux de la série carbonate du trias, localisés en Haute Silésie (Gliwice - GZWP 330, Lubliniec–Myszków - GZWP 327, Bytom - GZWP 329, Chrzanów - GZWP 452 et Olkusz–Zawiercie - GZWP 454). Pendant la valorisation nous avons employé la méthode ponctuelle en basant sur des critères principaux et secondaires. Parmi les critères principaux nous avons retenu la qualité des eaux et la susceptibilité des eaux souterraines à la pollution (degré d'isolation des réservoirs). Les critères secondaires comprennent: la déficience de réservoir exprimée par l'état des réserves de disposition, le rôle des eaux souterraines dans l'alimentation exprimée par la grandeur du captage et par la distinction des réservoirs qui sont la seule ou la plus importante source d'alimentation, l'indice des ressources exprimé par le module des ressources renouvelables. La valeur définitive d'un réservoir (W) nous calculons par la multiplication de l'index w, obtenu à base des critères principaux, par quatre facteurs (α, β, γ, δ) résultant des critères secondaires. Nous avons employé une classification à quatre degrés de la valorisation des réservoirs: A – une valeur très grande ($w > 15$), B – une grande valeur ($w = 10$–15), C – une valeur moyenne ($w = 5$–10), D – une petite valeur ($w < 5$). Selon les critères énumérés nous avons estimé que les réservoirs de très grande valeur sont: GZWP 327, GZWP 330 et GZWP 454; où le plus grand nombre des points a obtenu le réservoir Lubliniec–Myszków (GZWP 327). Parmi tous les cinq réservoirs étudiés la valeur la plus petite est déclarée pour Bytom (GZWP 329). En prenant en considération les résultats de la valorisation il faut admettre que les réservoirs les plus précieux (classe A et B) devraient bénéficier d'une protection spéciale et le captage des eaux devrait s'effectuer sous contrôle. La méthode de valorisation de GZWP présentée ici a un caractère estimatif, découlant avant tout des valeurs moyennées des facteurs calculés, qui nécessite un perfectionnement. L'identification des réservoirs les plus précieux devrait être un élément important, pris en considération dans la planification de la gestion des eaux et dans la protection plus efficace des ressources d'eaux souterraines dans l'échelle régionale.

First received: March 2001.

World Karst
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of the British Cave Research Association
Volume 32 (1), 2005

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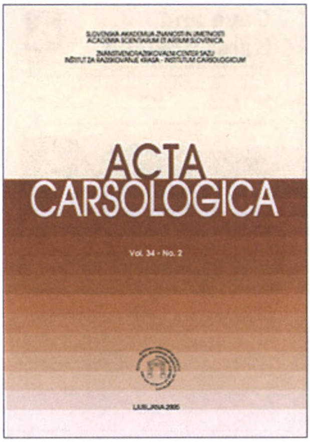

Acta Carsologica

Volume 34, 2, 2005

Slovenian Academy of Sciences and Arts, Scientific Research Center of the Slovenian Academy of Sciences and Arts, Slovenia

ISSN 0583–6050

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Volume 56(1–4), December 2005

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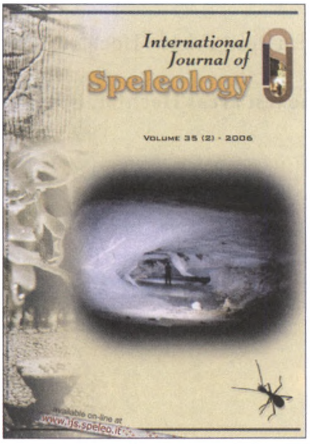

International Journal of Speleology

Volume 35(2), July 2006

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ISSN 0392–6672

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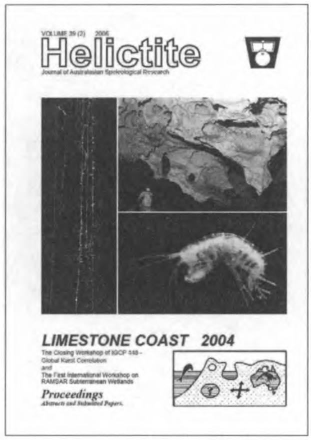

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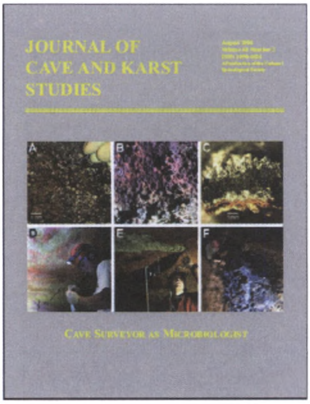

Journal of Cave and Karst Studies

Volume 68(2), August 2006

of the National Speleological Society

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Karstologia 47/2006

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Tiankengs: Special issue also published in Cave and Karst Science

(32, 2–3, 2005) and Carsologica Sinica (25, 2006)

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ISSN 0208-6336
ISSN 0137-5482

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Wydawnictwo Uniwersytetu Śląskiego
ul. Bankowa 12B, 40-007 Katowice
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Wydanie I. Nakład: 250 + 50 egz. Ark. wyd. 10,5. Ark. druk. 8,5 + wklejka. Przekazano do drukarni w maju 2007 r. Podpisano do druku w styczniu 2008 r. Papier offset. III kl. 80 g Cena 18 zł

„EXPOL", P. Rybiński, J. Dąbek, Spółka Jawna
ul. Brzeska 4, 87-800 Włocławek

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ISSN 0208-6336
ISSN 0137-5482