Developments in Earth Surface Processes 1

PALEOKARST

a systematic and regional review

Edited by

PAVEL BOSÁK
Geoindustria, Prague, Czechoslovakia

DEREK C. FORD
Department of Geography, McMaster University,
Hamilton, Canada

JERZY GŁAZEK
Institute of Geology, Warsaw University,
Warsaw, Poland

IVAN HORÁČEK
Institute of Geology and Geotechnics, Czechoslovak
Academy of Sciences, Laboratory of Quaternary
Geology,
Prague, Czechoslovakia

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PALEOKARST OF POLAND

Jerzy Głazek

Introduction

Numerous *fossil karst* phenomena have been reported in Poland. However, this information has generally been obtained during other investigations in geology, geomorphology, paleontology or archeology. Only a few paleokarst localities have been thoroughly studied in their own right.

Data on the fossil karst of Poland have been reviewed many times (GILEWSKA, 1964, 1971; GRADZIŃSKI and WÓJCIK, 1966; GŁAZEK, DĄBROWSKI and GRADZIŃSKI, 1972; GŁAZEK, 1973, 1975). Some of the reviews discuss the difficulties in interpreting *fossil karst* that are essentially caused by the possibility of karstification taking place beneath less soluble or insoluble strata (GRADZIŃSKI and WÓJCIK, 1966; GŁAZEK, 1973). Nevertheless, paleokarst studies have considerably supplemented our knowledge on the paleogeographic development of different areas, especially of platform regions where the current paleogeographic syntheses are constructed by interpreting marine or large continental formations that occupy less than 50 % of the geological time span. Within the time stratigraphic gaps, deposits are often preserved as a fill of karst forms. These have recorded very important data for paleogeographic speculation, but they need special care during investigations (QUINLAN, 1972; GŁAZEK, 1973). In earlier reviews (GILEWSKA, 1964; GRADZIŃSKI and WÓJCIK, 1966) paleokarst phenomena were treated differently in each present-day geomorphic unit of Poland. The present author introduced paleogeographic treatment of the entire country, in which paleokarst forms are a very important source of information that enables reconstructions of past scenery (GŁAZEK, DĄBROWSKI and GRADZIŃSKI, 1972; GŁAZEK, 1973; GŁAZEK and SZYNKIEWICZ, 1987).

Among the papers concerning paleokarst features in Poland, the first outstanding example is the description of a vertical shaft in Węże that was filled with Pliocene sediments containing a rich collection of vertebrate fossils (SAMSONOWICZ, 1934). Before that, in the 19th Century, vertebrate remains and artifacts excavated in caves were thoroughly studied (ROMER, 1883; OSSOWSKI,

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1882). Since 1950 there have been descriptions of (i) deposits containing reptile bones in a Triassic cave at Stare Gliny (LIS and WÓJCIK, 1960; TARLO, 1959) and in Czatkowice (PASZKOWSKI and WIECZOREK, 1982), (ii) the polyphase development of underground karst forms in the Cracow Upland (GRADZIŃSKI, 1962), (iii) orefilled hydrothermal karst forms in Triassic carbonates of the Cracow-Silesian ore district (BOGACZ, DŻUŁYŃSKI and HARAŃCZYK, 1970; DŻUŁYŃSKI and SASS-GUSTKIEWICZ, 1982, p. 377–397), (iv) vertebrate and beetle-bearing Miocene karst deposits at Przeworno (GŁAZEK, OBERC and SULIMSKI, 1971; GALEWSKI and GŁAZEK, 1973; GŁAZEK, GALEWSKI and WYSOCZAŃSKI-MINKOWICZ, 1977; GŁAZEK et al., 1975). Very useful data for the reconstruction of the Late Pleistocene landscapes have been obtained from interdisciplinary studies of archeological excavations in caves (MADEYSKA, 1981, 1982).

Biostratigraphic dating of karst deposits was introduced by SAMSONOWICZ (1934) and later broadly developed (KOWALSKI, 1962, 1964; SULIMSKI, 1964; GŁAZEK, OBERC and SULIMSKI, 1971; BOSÁK et al., 1982; GŁAZEK and SZYNKIEWICZ, 1987). It was supplemented by semiquantitative bone-dating using complex fluorine-chlorine-apatite and collagen methods (WYSOCZAŃSKI-MINKOWICZ, 1969). The first isotope dating of charcoal from Late Pleistocene cave deposits was done by the ^{14}C method for archeological purposes in 1960 (Gro-2118, *fide* MADEYSKA-NIKLEWSKA, 1969). Later, it was extended for speleothem dating by the $^{230}Th/^{234}U$ method (GŁAZEK and HARMON, 1981, in press). Currently speleothem and bone datings using ^{14}C, thermoluminescence (TL) and electron spin resonance (ESR) methods are being introduced (HERCMAN et al., 1987).

Interest in paleokarst has been much increased in Poland because of mining, foundation engineering and dam construction problems (BAŻYŃSKI, 1960; KRASOŃ and WÓJCIK, 1965; WILK, MOTYKA and NIEWDANA, 1973; GŁAZEK and SZYNKIEWICZ, 1979; MOTYKA and WILK, 1984; WILK, p. 513–531).

Remarks on Terminology

In Polish scientific literature only one term — *kras kopalny* is used. It is translated as *fossil karst* but may be treated as a synonym for *paleokarst* in the English language literature. Currently, all forms evidently older than the last distinguishable glacial deposits in an area are treated as paleokarst in Poland. This criterion is diachronous because in southern and central Poland the youngest glacial deposits are of Middle Pleistocene age, while in the northern part of the country and in the highest mountains on the southern border, the latest glaciation is Late Upper Pleistocene (Vistulian, Würm).

The German term *subrosion* has been adopted in Polish literature for the underground solution of evaporites (POBORSKI, 1957); it is a type of subjacent karst. The term *hydrothermal karst* was introduced for "underground karst features produced by the action of hydrothermal solutions" by BOGACZ, DŻUŁYŃSKI and HARAŃCZYK (1970) in their discussion of the origin of the Cracow-Silesian zinc-lead deposits.

The term *phase of karstification* was used in a broad sense (GŁAZEK, DĄBROWSKI and GRADZIŃSKI, 1972; GŁAZEK, 1973, 1975) that is equivalent to the term *period of karstification* adopted in this book. Similarly, *stage of karstification* was used where *phase of karstification* is being used here.

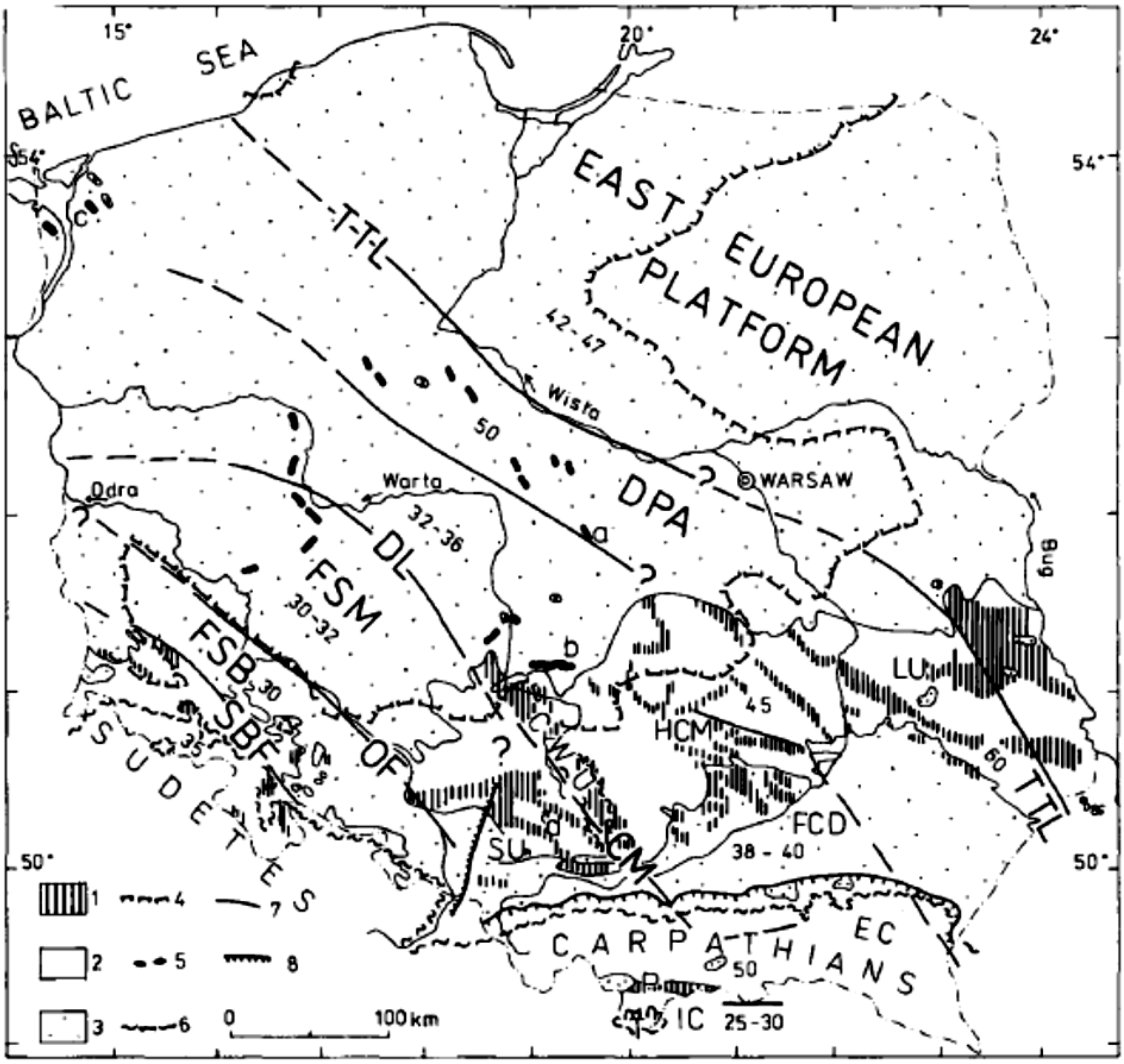
The Geologic Frame of Karst Development

In Poland all the main tectonic realms of Europe are brought into contact (Fig. 2–25). The younger overlap the older (PEIVE et al., 1981, 1982; KSIĄŻKIEWICZ, OBERC and POŻARYSKI, 1978). In the north-eastern part of the country is the SW slope of the ancient East European Craton (Platform; abbreviated EP); the southern part belong to the Alpine Orogen of the Carpathians and the south-west part to the young epi-Variscan Central European Platform (CEP). This general division is widely accepted but the boundaries between these principal units are not universally agreed. The published opinions were strongly influenced by the now rejected "geosynclinal" theory. In the present writer's view, between the well established realms mentioned above there exists a stable continental margin of the European Craton that has been slightly affected by every younger tectonic event known in the development of the present European continent.

The undisputed EP is north-east of a deep fracture zone called Teisseyre-Tornquist Line (TTL) and consists of Proterozoic (Gothian?) crystalline basement covered with 0.5 to 5.0 km of flatlying, slightly faulted and tilted sediments of Late Precambrian to Cenozoic age. Scattered among the dominant siliciclastics are some interbedded carbonates and sulfates as well as numerous breaks in deposition. Only a few karst landforms are known at outcrop, in the Late Cretaceous chalk and limestones (MARUSZCZAK, 1966). Some subsurface karst features have been found in boreholes and mines in Devonian, Lower Carboniferous and Upper Jurassic limestones (ŻELICHOWSKI, JUSKOWIAKOWA and MIŁACZEWSKI, 1974; SKOMPSKI, 1985).

The CEP, which forms the north-eastern slope of the Bohemian Massif extends to a deep fracture zone termed the Dolsk Line (DL; GUTERCH, 1977; SPECZIK, 1985) and to the western boundary of the Upper Silesian Coal Basin (Fig. 2–25). The pre-Namurian metamorphic basement of the Bohemian Massif (VAN BREEMEN et al., 1982) which crops out in the Sudetic Mountains and fore-Sudetic Block (FSB), contains many graben with siliciclastics of Carboniferous, Permian, Triassic and Cretaceous age. From the Odra Deep Fracture (OF), this basement deepens to the north-east under epicontinental Late Carboniferous to Cretaceous sedimentary cover.

Within the complicated structure of the Late Precambrian and Paleozoic metamorphic sequences of the Sudetes and FSB, steep and fractured marble lenses occur that are strongly karstified. Flat post-Variscan cover on the north-eastern slope of this area contains the Zechstein evaporite-carbonate sequence, Muschelkalk carbonate-sulfate rocks and some limestones of Upper Jurassic and Upper Cretaceous age. These rocks are karstified to a considerable depth (KRASOŃ and WÓJCIK, 1965), the karstification having taken place during several periods of subaerial weathering.

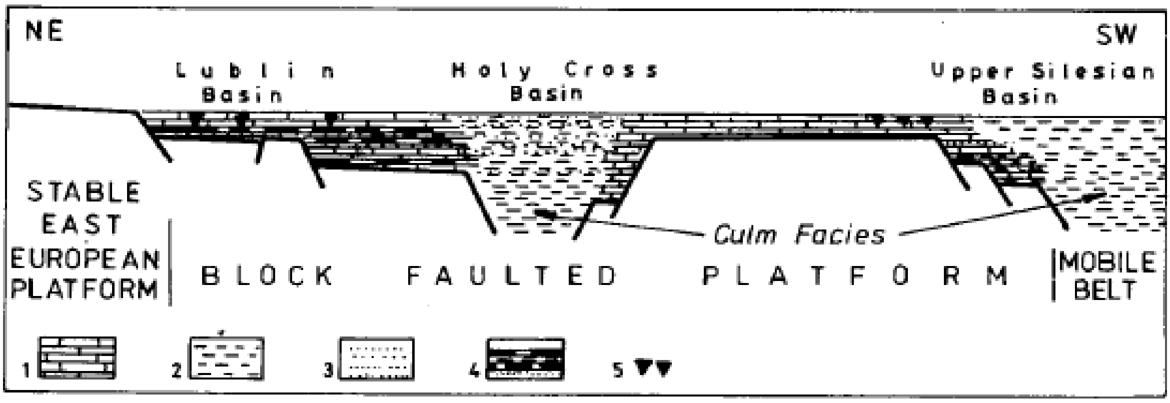


2–25. Geotectonic and geomorphic setting of karst in Poland. Areas of: 1. karstified rocks; 2. insoluble or slightly soluble rocks; 3. thick Cenozoic overburden; 4. subcrops of Zechstein (Late Permian) evaporites; 5. subrosion depressions with thick Cenozoic deposition; 6. maximal extent of Pleistocene glaciations; Tectonics: 7. deep-fracture zones (TTL = Teisseyre-Tornquist Line, DL = Dolsk line, OF = Odra Fault, SBF = Sudetic Border Fault, CM = Cracow-Myszków Fracture Zone). Main crustal blocks (figures represent recognized depth of Moho discontinuity according to GUTERCH, 1977): DPA = Danish-Polish Aulacogen (rift zone), FSM = fore-Sudetic Monocline, FSB = fore-Sudetic Block; 8. frontal overthrusts of Variscan and Alpine Orogens. Geomorphic units: Uplands of Meta-Carpathian Arch: SU = Silesian Upland, CWU = Cracow-Wieluń Upland, HCM = Holy Cross Mountains, LU = Lublin Upland; FCD = fore-Carpathian Deep; Carpathian Orogen: EC = External Carpathians, IC = Internal Carpathians, P = Pieniny Klippen Belt, T = Tatra Mountains.

Between the TTL and DL zones the basement is poorly known. It is believed to be of Late Precambrian age because slightly metamorphosed shales are found in numerous boreholes in the foreland of the Carpathians, beneath the Upper Silesian Coal Basin and Carpathian frontal overthrust (ŚLĄCZKA, 1976). The shales are covered by flat-lying fossiliferous Lower Cambrian rocks (ORŁOWSKI, 1975) and pass to the south-west (beneath the West Carpathians and in Moravia) into the Brno crystalline massif of the same age (VAN BREEMEN et al., 1982). This whole basement (called

Bruno-Vistulicum by DUDEK, 1980) may be treated as the block-faulted (mobilized) margin of the ancient European Craton. Within its boundaries, along the south-western side of the TTL there is a trough named the Danish-Polish (–Dobrogean) Aulacogen (DPA; GUTERCH, 1977). The trough existed from the Early Permian until Late Cretaceous times (KUTEK and GŁAZEK, 1972; GŁAZEK, TRAMMER and ZAWIDZKA, 1973; POŻARYSKI and BROCHWICZ-LEWIŃSKI, 1978). Probably it originated much earlier and may be considered an *aborted* Cadomian rift on which were superimposed the similar younger rifts of the Alpine cycle. Slight folding and faulting occurred there during every younger tectonic event that affected the development of the European continent. Finally, the aulacogen was inverted into the Mid-Polish Anticlinorium at the end of Cretaceous and beginning of Paleogene times (KUTEK and GŁAZEK, 1972).

The platform was invaded by the sea several times. From the Lower Cambrian onwards these transgressions left epicontinental siliciclastics or carbonate deposits and some evaporites. A thick epicontinental carbonate sequence with some sulphates and dolostones in its lower part was deposited from Early Middle Devonian to Early Carboniferous (GŁAZEK et al., 1982; SZULCZEWSKI, 1971; NARKIEWICZ, 1979, 1985; BEŁKA, 1987; SKOMPSKI,1985). Syndepositional faults were active (SZULCZEWSKI, 1973, 1978) and the area was differentiated into uplifted and subsided blocks, then gradually uplifted together with the Variscan Orogen in Late Carboniferous-Early Permian times. At that period karstification was common. It started as a syngenetic process on the rising blocks (SKOMPSKI, 1985; BEŁKA, 1987; Fig. 2–26). Although this karstification period was long and general throughout the whole country, evidence of it is poor due initially to the clastic overburden of Late Carboniferous regressive and deltaic deposits and then to the prevailing arid climate in the Permian (MROCZKOWSKI, 1982) and finally to later erosion.

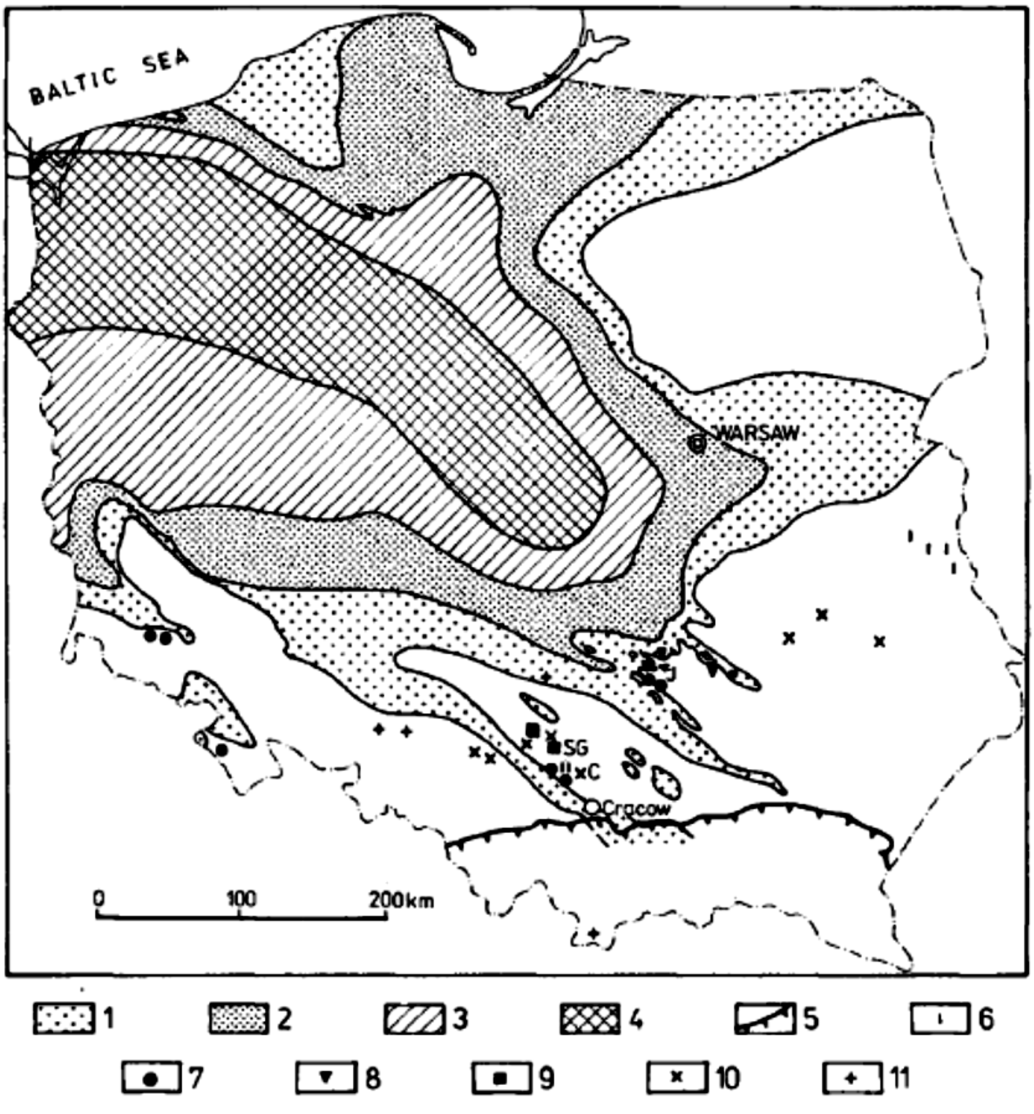


2–26. Schematic section showing the pattern of Late Visean marine deposits in Poland, not to scale (modified after SKOMPSKI, 1985). 1. carbonates; 2. claystones; 3. sandstones; 4. coal measures; 5. traces of syngenetic karst forms.

The next transgression followed Variscan movements in the Late Permian times. There was catastrophic flooding of the Variscan foredeep (D. B. SMITH, 1970; MROCZKOWSKI, 1982) by the Zechstein Sea which left a thick carbonate-evaporite sequence passing gradually into the continental siliciclastics of the Lower Triassic. They were gradually submerged and covered by the limestone-dolostone-sulphate deposits of the Röt and Muschelkalk seas (GŁAZEK, TRAMMER and ZAWIDZKA, 1973). After gradual retreat in the late Middle Triassic, continental conditions prevailed until the widespread Late Jurassic transgression began. The Upper Jurassic limestones are the second outstanding karst formation, after that of the Devonian. In the Tithonian, the sea retreated again and the Early Cretaceous was a period of continental erosion. Karstification from that time is poorly evidenced, probably due to the clayey-marly character of the uppermost Jurassic and Berriasian-Hauterivian rocks which, in addition, are preserved only in a limited belt along the DPA axis (KUTEK and GŁAZEK, 1972; GŁAZEK, 1973).

The Albian-Cenomanian transgression covered the whole platform area and left mainly the low permeability, microporous chalk and marl deposits of the Upper Cretaceous. They are only feebly karstified (MARUSZCZAK, 1966).

In general, thicknesses and facies patterns on the platform of Permian-Mesozoic times suggest that interference from two structural directions affected the sedimentation and vertical movements. First there is an axis of subsidence along the DPA, with rapid thinning of sediments to the north-east and moderate thinning to the south-west of it. The deepest facies and more complete sequences occur along the subsidence axis, while there are shallower facies and longer breaks on the limbs of the trough (KUTEK and GŁAZEK, 1972). On the north-eastern limb and from the north along the axis of the DPA, the massive terrigenous influx from elevated parts of the EP is remarkable, while on the



2-27. Distribution of Late Paleozoic and Mesozoic karst in Poland. 1. Extent of Permian deposits: Rotliegendes and thin Zechstein (200 m), showing NW-SE rift pattern controlling the Early Permian continental sedimentation; 2–4. thickness of Zechstein evaporite sequence showing typical thickness pattern of Late Permian and Mesozoic deposits (slightly altered by later erosion): 2. 200–500 m, 3. 500-1 000 m, 4. over 1 000 m; 5. northern margin of the Carpathian nappes; 6. syngenetic Visean karst; 7–11. subaerial karst buried with deposits of: 7. Permian, 8. Bunter, 9. Middle Triassic, 10. Late Triassic-Middle Jurassic, 11. Albian-Cenomanian.

south-eastern limb rather open marine carbonate deposition dominated. Clastic material carried from elevations of the Bohemian Massif is visible in the Upper Cretaceous, absent in the Upper Jurassic and only feebly present in the Middle Triassic.

The Permian-Mesozoic cover is stratigraphically more complete along the subsidence axis than further southwest and north-east. Some deposits preserved near the axis wedge out completely to the southwest and northeast of it. The Mid-Polish Anticlinorium began to rise in Late Maestrichtian times, together with broad regression on its southwestern limb. Regressive deposits of Late Maestrichtian and Paleocene age are known in the northern and eastern parts of the country, where remnant basins persisted until the Montian. Brown coal deposits of Late Paleocene to Early Eocene age (CIUK, 1974) are known in subrosion depressions on the Mid-Polish Anticlinorium and on its southwestern limb (cf. Fig. 2–25).

The second structural pattern is associated with the evolution of the Tethyan realm and is thus marked by east-west axes. The Mesozoic subsidence axis of the Central European Basin lies a little north of Warsaw, but the uplift axis migrated from south to north during the growth of the Tethyan stable continental margin. The earlier Permo-Triassic site of this axis (known as the Vindelician Arch) was covered by Carpathian overthrusts and partly consumed in subduction beneath the Carpathian Orogen. During subsequent transgressions, the arch was last to be inundated and so was covered with relatively thin and shallow deposits. The latest position of this arch (after the regression of the Sarmatian Sea) is called the Meta-Carpathian Arch and is visible in the present morphology as a Mid-Polish Upland Belt stretching from the Bohemian Massif through the Sudetes, Silesian-Cracow Upland, Holy Cross Mountains and Lublin Upland to the Volhynia and Podolia. Numerous paleokarst features of different ages are visible in this belt of uplands (Figs. 2–25, 2–27 and 2–36).

On the southern slope of the Vindelician Arch in the area of the Inner Carpathians (IC) (south of the Pieniny Klippen Belt, CP) sedimentation began on the crystalline Variscan basement. Upper Permian or Lower Triassic clastics pass upward into shallow marine carbonates deposited on a stable continental margin after the late Early Triassic. These carbonates are the oldest karst formation in the Tatra Mountains. Late Triassic to Middle Jurassic extension of the lithosphere led to strong facies differentiation and local breaks in the region. As a result, from the Middle Jurassic onwards, deep sea facies (radiolarites) were deposited in the troughs (the Pieniny and Subtatric sequences), while on the elevated blocks of the High Tatric sequence thick pelagic limestones were laid down. Deposition of this sequence continued until Early Cretaceous times, when it was replaced by a shallow Urgonian facies. These limestones are the second in stratigraphic order but are the most important karst formation in the Tatra Mountains. On the top of the Urgonian limestones traces of syngenetic karstification were noted by PASSENDORFER (1930). Immediately after its deposition, in the Albian times, the Urgonian carbonate platform was drowned and covered with pelagic limestones, marls and distal turbidites which terminate in the Turonian. Later, the area was folded and elevated. Subsequent erosion lasted until Middle Eocene times when, following brief deposition of Eocene conglomerates and carbonates, turbidites of Oligocene age covered the whole Tatric area. Lenses of red continental conglomerates at the base of the Eocene sequence are known but no apparent paleokarst forms have been described. However, some karstification is highly likely and frequently suggested by many authors. From the Late Jurassic to the Early Miocene, the Inner Carpathians were bordered on the north by a zone of siliciclastic turbidite sedimentation from the Outer Carpathians (EC).

Epicontinental seas connected with the North Sea Basin and the Tethyan Basin of the Middle Eocene invaded most of the platform areas in Poland (POŻARYSKA and ODRZYWOLSKA-BIEŃKOWA, 1977). They covered the older erosional landscape with its continental deposits retained in subrosion depressions with marly, glauconitic sands and silts. Regression at the Eocene-Oligocene boundary reduced this sea to a remnant in the northeastern corner of Poland (ODRZYWOLSKA-BIEŃKOWA, POŻARYSKA and MARTINI, 1978), while the rest of the country was covered either by tidal flat and delta deposits or was eroded. Numerous karst forms developed in central and southern Poland.

Some of them are well dated by vertebrate remains and the Lower Badenian overburden (Fig. 2–36). Thick brown coal deposits accumulated within subrosion depressions in western and central Poland prior to the Badenian transgression. The paleogeographic pattern of the Middle Miocene was governed by the subsidence of the Carpathian Foredeep. The sea invaded most of the platform part of Poland and deposited thick clays and silts in the south. Shallow marine deposits in the Carpathian Foredeep passed to the north in to alluvial plain deposits derived from Scandinavian rivers. These covered the Oligocene-Lower Miocene karst landscapes (GŁAZEK and SZYNKIEWICZ, 1987). Between the alluvial plain and the open marine facies, biocalcarenites and algal-vermetid reefs were deposited on the southern slope of the Mid-Polish Uplands while sands were laid down around river mouths (RADWAŃSKI, 1969, 1973; KARNKOWSKI, 1985; PISERA, 1985). A local salinity crisis in the Middle Badenian during a slow subsidence of the continental margin resulted in gypsum sedimentation in the northern part of the marine basin and halite precipitation near the Carpathian margin.

Lower Badenian marine sediments as well as slightly older and youger continental deposits were also deposited on the EC and then slightly folded and thrusted by forces associated with the Carpathian nappes (BAŁUK, 1970). The Carpathian Orogenic Belt was strongly folded and thrust on to its foredeep during the Middle Miocene times. These movements probably began beneath sea level during Early Miocene times. The Orogenic Belt was uplifted and its erosion began (BURCHART, 1972).

Later, during Late Badenian and Sarmatian times, alluvial plain deposits gradually overlapped the marine deposits of the Carpathian Foredeep. Such a situation is seen in Lower Silesia, while on the more elevated uplands only outliers of Middle Miocene deposits are preserved on hill-tops, in buried valleys or trapped in karst depressions (Fig. 2–36). Strong erosion and exhumation of the pre-Middle Miocene relief took place after deposition of the brackish Sarmatian strata. This erosion was accelerated by the Messinian crisis, when the erosional base level in the Black Sea area was lowered to –1 600 m (HSÜ and GIOVANOLI, 1979) and then by Pliocene uplift of whole area (GŁAZEK and SZYNKIEWICZ, 1987). A new river pattern developed on the flat surface of the Middle Miocene deposits (DŻUŁYŃSKI et al., 1966). This pattern was partly affected by the pre-Middle Miocene depressions after the Miocene strata had been eroded. Because of this, numerous Late Neogene river valleys were abandoned and became filled with the so-called *preglacial deposits* (clastics) of Pliocene and Early Quaternary age. Just before the continental glaciers reached Poland, and as a result of further uplift of the Carpathian Orogen with its foreland, a new river pattern consequent to the newly created Baltic depression was formed and drainage to the Black Sea ceased (DŻUŁYŃSKI et al., 1968).

The Polish Lowland has been covered by continental ice sheets several times since the beginning of the Brunhes Epoch. The maximum extent of erratic boulders and till reaches the Carpathian slopes (Fig. 2–25). This maximum glaciation is called the Sanian Glaciation and correlates with the Elsterian to the West. Not less than three younger and less extensive glaciations (Odranian, Wartanian and Vistulian) are preserved at the surface. In addition, from subsurface evidence, a further one or two glaciations older than the Sanian and one or two younger (between the Sanian and the Odranian) are suggested but much disputed (RÓŻYCKI, 1979; LINDNER, 1984; MOJSKI, 1985). Well-dated cave deposits of glacial and interglacial origin contribute considerably to this discussion (GŁAZEK, LINDNER, WYSOCZAŃSKI-MINKOWICZ, 1976; GŁAZEK et al., 1976, 1977; GŁAZEK and HARMON, 1981).

The highest mountains on the southern border were also glaciated. There were at least three glaciations in the Tatras (Fig. 2–25). The latest one was well dated in the Magura Cave using the ^{14}C method at between 23 and 11 ka (HERCMAN et al., 1987). In the Karkonosze Group of the Sudetic Mountains traces of one glaciation are visible, probably the youngest one.

Periods of Karstification

The intricate geologic development of the Polish territory has resulted in several periods of karstification and, within these general periods, many particular phases or events of karstification can be distinguished.

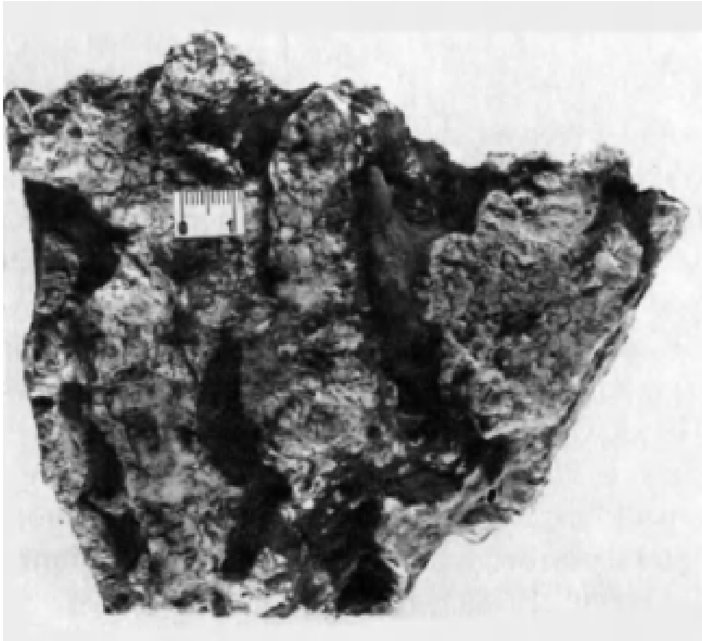
First Period of Karstification; Early Carboniferous to Middle Triassic

The oldest period of karstification followed the decline of carbonate sedimentation in the Late Visean and lasted until the inundation of the post-Variscan landscape by the Muschelkalk sea. So far, the oldest phase identified within that period is Late Visean. It is recognized in the subsurface of the Lublin Upland and in the vicinity of Cracow, on elevated blocks of tectonically extended carbonate platforms (Figs. 2–26 and 2–27). Syngenetic karst activity is demonstrated by minor corrosion, vadose cements, and paleosoils with burrows and rhizoliths (SKOMPSKI, 1985; BEŁKA, 1987).

The next phase of karstification is characterized by red breccias, conglomerates, sandstones and siltstones filling sinkholes, vertical shafts and horizontal caves. These are common and described from: (i) the Holy Cross Mountains in Devonian carbonates (cf. GUIDE, 1978); (ii) the vicinity of Cracow in Visean limestones (SIEDLECKI and WIESER, 1948; PASZKOWSKI and WIECZOREK, 1982); (iii) the Sudetes in (?) Paleozoic marbles (GIERWIELANIEC and SZTUK, 1977; Z. BARANOWSKI and S. LORENC pers. comm., 1985).

In Czatkowice Quarry (C in Fig. 2–27) layered rhyodacite tuffites filling a large cave are intercalated with calcite and silica flowstone layers (PASZKOWSKI and WIECZOREK, 1982). All these forms are found near the edges of similar Rotliegendes deposits filling synsedimentary troughs (Fig. 2–27). The tuffites may be correlated with violent volcanic activity along the faults of neighbouring graben that filled with fanglomerates and rhyodacite tuffs during the Lower Permian. The deposits are found in corrosional caves and shafts of similar or slightly older age. Their age seems to be younger than the Westfalian coal-bearing sediments but older than the Zechstein transgression.

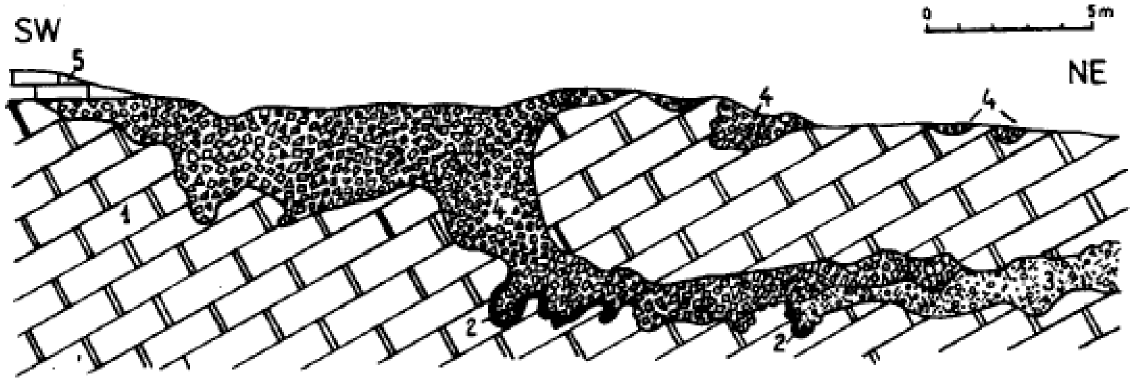
Within the Zechstein evaporite sequence in the subsurface of the Polish Lowland, borehole and seismic data plus a few observations in mines, reveal anomalous thinning or wedging out of the evaporite layers. These phenomena were interpreted as products of major subaerial karstification between particular salt cycles (KRASOŃ and WÓJCIK, 1965; POBORSKI, 1975). However, there are great difficulties in discriminating between the effects of early (syngenetic) and considerably younger (subjacent, in this case subrosional) karstification. More-over, great changes of thickness in salt layers were caused by subaquatic dissolution (resulting from brine dilution in the lagoonal environment as a consequence of freshwater influx) and by salt migration. Nevertheless, detailed studies of borehole profiles have produced evidences of synsedimentary dissolution, soil formation and vadose (intertidal ?) diagenesis in the Zechstein rocks (PERYT, 1984). That means that at least some phases of syngenetic karstification occurred during the Zechstein sedimentation. These are contemporaneous with one karstification phase outside of the Zechstein basin.



2–28. Solution runnel on the Givetian limestones filled with Bunter siltstones at Jaworznia Quarry (J in Fig. 2–27), scale is 1 cm. (Photo by K. Boruta).

A subsequent karstification phase is recognized beneath Bunter deposits on the top of Devonian carbonates in several localities in the Holy Cross Mountains. At Jaworznia Quarry (J in Fig. 2–27) there are sinkholes, meandering solution runnels (Fig. 2–28) and solution pans filled with red siltstones (GŁAZEK and ROMANEK, in GUIDE, 1978). This phase is clearly separated from the older one only in the NW part of the HCM area where along the subsidence axis of the DPA, Bunter deposits were laid down with lithologic continuity onto the Zechstein.There, during the Bunter sedimentation, some Devonian carbonates became exposed to karstification along the uplifted edges of synsedimentary tilted blocks (KUTEK and GŁAZEK, 1972; GŁAZEK and ROMANEK, in GUIDE, 1978).

The last phase of karstification occurred along the Cracow-Myszków fracture zone. It is best represented at Stare Gliny Quarry (SG in Fig. 2–27 and Fig. 2–29) where a cave with bone breccia in a fossil (?) mogote of Devonian dolostones has been described (LIS and WÓJCIK, 1960). The fauna includes fish teeth and scales (*Gyrolepis, Saurichtys, Coelacantiformes*), as well as reptilian bones and skulls from the small archosaurs *Macrocnemus* and (dominant in this assemblage) *Nothosaurus* (TARLO, 1959). The bone-bearing layer is covered with a breccia of angular blocks of Devonian dolostones in a ground mass of Middle Muschelkalk (Late Anisian) *Diplopora* dolostones. This littoral cave was quickly destroyed and covered with shallow water deposits during structural remodelling of the Muschelkalk sea in the Illyrian (GŁAZEK, 1973; GŁAZEK, TRAMMER and ZAWIDZKA, 1973).



2–29. Section of the western wall of the Stare Gliny Quarry (SG in fig. 2–27) showing a paleokarst cave of Triassic age (after LIS and WÓJCIK, 1960). Middle Devonian: 1. dolostones; Middle Triassic: 2. residual clays, 3. cave deposits with reptilian bones, 4. breccia of Devonian dolostones within *Diplopora* dolostone (Middle Muschelkalk), 5. *Diplopora* dolostones.

The paleogeographic conditions were variable during this first karstification period. A wet and hot climate, resembling the present tropics, may be suggested for the flat coastal plains of the Lower Carboniferous. Probably similar conditions were dominant on the emerged edges of the tilted blocks of Frasnian carbonates in the HCM area. The two following phases developed under a semi-arid or arid climate, similar to recent deserts, with torrential mudflows and ephemeral streams in diversified, hilly landscapes. The last phase is represented by isolated dolostone islands that emerged from the shallow marine Middle Muschelkalk basin with its hypersaline characteristics. These hills were interpreted as inundated mogotes overlooking a corrosional plain on the Devonian carbonate rocks. However, they can be interpreted as emerged edges of tilted blocks thrown up during the Middle Triassic extension of the continental margin. Hot and rather dry conditions may be ascribed to this phase.

Second Period of Karstification; Late Triassic to Middle Jurassic

This period is represented at the surface in the Silesian and Cracow Upland and in the subsurface in the Lublin Upland. On the northeastern slopes of the Silesian Upland, in Triassic carbonates and beneath Quaternary deposits, there are narrow depressions up to 30 m deep and 2 km long (GÓRZYŃSKI, 1963;

GILEWSKA, 1965). They are filled with variegated clays, silts and sands. Among the deposits are (i) thin intercalations (10 cm) of black carbonaceous clays yielding lowermost Jurassic spores; (ii) halloysite beds up to 50 cm thick, and (iii) layers of boehmite-alunite clays up to 50 cm thick (GÓRZYŃSKI, 1963). These deposits are interpreted as Lower Jurassic fillings of karst features. However, they are hardly distinguishable from Tertiary subjacent karst forms with subsided Lower Jurassic rocks (GILEWSKA, 1965).

In Czatkowice Quarry (C in Fig. 2–27) there are karst cavities filled with grey sandstones and siltstones intercalated with thick, coarse crystalline flowstones. They contain reptilian bones and skulls that are not fully studied yet, but are of uppermost Triassic-Lower Jurassic appearance (PASZKOWSKI and WIECZOREK, 1982). The trends of these cavities are parallel to a neighbouring fault of pre-Callovian age. Similar grey sandy deposits with reptilian bones were found later in a debris heap at Stare Gliny Quarry (K. ZAWIDZKA, pers. comm., 1985). According to F. WESTPHAL (pers. comm., 1985) these bones represent younger reptiles than those described earlier by TARLO (1959). It is very probable that they were excavated from a small karst depression noted in the top of *Diplopora* dolostones beneath Callovian deposits (LIS and WÓJCIK, 1960).

The karstified top of the Devonian carbonates was noted in some deep boreholes in the Lublin Upland. Variegated clays with chaotic blocks of Devonian limestones are covered by flat-lying Bathonian (?) transgressive deposits (GŁAZEK and MATYJA, unpubl. 1974; ŻELICHOWSKI, JUSKOWIAKOWA and MIŁACZEWSKI, 1974). In this area a pattern of river valleys cut in the Paleozoic strata and filled with Lower Jurassic clastics was found (SZYDEŁ and SZYDEŁ, 1981). Thus, a buried karst of Lower to early Middle Jurassic age is very probable in this region.

The second period of karstification commenced after regression of the Middle Triassic sea and ended with the Middle Jurassic transgression. This karstification was caused by the old Cimmerian movements. It was well developed on both limbs of the DPA, where regressive Keuper deposits were eroded prior to the Middle Jurassic (Bathonian-Callovian) transgression. Rhaetian and/or Lower Jurassic continental to near-shore deposits are absent or considerably less well developed than along the axis of the DPA.

At that time, in a hot and humid climate, a landscape of gentle hills developed on the flanks of the DPA. Probably this period should be divided into two or more distinct phases of karstification but stratigraphic evidence is insufficient as yet.

It is believed that the subsurface processes that formed the zinc-lead deposits of the Upper Silesian-Cracow ore district belong to this period, especially the earlier stages distinguished by SASS-GUSTKIEWICZ (1985): "dolomitization of Muschelkalk limestones" and the "non-integrated circulation of ore-forming fluids" (DŻUŁYŃSKI and SASS-GUSTKIEWICZ, p. 377–397). Probably the next phase of "phreatic integrated solution transfer" also occurred before erosion of the clayey Keuper overburden. After erosion of the Keuper clays, travertines (Woźniki Limestones) were deposited in places on the surface among the Rhaetian variegated clays. These travertines are believed to have been deposited at springs which discharged the ore-depositing fluids (BOGACZ, DŻUŁYŃSKI and HARAŃCZYK, 1970). Their age may therefore indicate the late phases of the ore deposition, namely "sudden drop of pressure and temperatures" and the beginning of "vadose ore precipitation" (DŻUŁYŃSKI and SASS-GUSTKIEWICZ, p. 377–397). Thus, the period of principal ore formation may be ascribed to the time span between the mid-Ladinian facies change from calcareous to marly and clayey regressive deposits (GŁAZEK, TRAMMER and ZAWIDZKA, 1973) and the mid-Rhaetian precipitation of the Woźniki Limestones. That is nearly 25 Ma according to ODIN's (1982) time-scale. The hydraulic head responsible for this deep groundwater circulation, its pressure and temperature, can be explained by infiltration from the northern slope of the Vindelician Arch into older Paleozoic carbonates and sandstones already exposed by the Late Carboniferous-Early Triassic erosion. This deep, confined water circulation supposedly dissolved heavy metal compounds dispersed in Paleozoic bituminous and coal-bearing sediments as well as in igneous rocks, and carried them up-dip along the fractures of the Cracow-Myszków zone to the confined Muschelkalk carbonate aquifer. This hypothesis is supported by the more diversified ore mineralization noted along some fracture lines in the Paleozoic rocks beneath ore-bearing dolostones of the Triassic (GÓRECKA, 1972).

With the erosion of the Keuper rocks, the metalliferous aquifer in the Muschelkalk became partly unconfined. This probably caused the drop of pressure and temperature and, as a consequence, the rapid sulphide precipitation. At that time, "vadose" conditions were probably established for the first time in the ore-bearing strata and some dripstones may have been deposited. However, there was no major infiltration of oxidized water because the sulphides remained stable. Some further stages in the development of the ore deposits, with alternating phreatic and vadose conditions, resulted in insignificant ore redistribution (SASS-GUSTKIEWICZ, 1985).

LIPIARSKI (1971) described some intercalations of coal among internal sediments in the ore-bearing cavities. These coals contain arthropod and plant remains of Mesozoic appearance. They suggest infiltration of surface water into the ore deposits. Later, in Middle Jurassic times, the whole area was buried by transgressive sediments and the zinc-lead deposits were probably inert until the next period of karstification.

Finally, some authors have suggested that there was Late Triassic-Middle Jurassic karstification in the High Tatric sequence. However, there are numerous neptunian dykes of Middle Jurassic age as well as Fe–Mn encrustations on the drowned Triassic carbonate platforms and no evident paleokarst forms.

Generally, changing climatic conditions may be suggested during this period of karstification, from warm and semi-arid in the Late Triassic to warm and humid in Early and Middle Jurassic times.

Third Period of Karstification; (?) Tithonian-Cenomanian

Late Cimmerian movements caused broad regression of the Upper Jurassic sea in the platform area of Poland and extensive subsidence of its southern margin where, from the Tithonian until the Lower Miocene, huge turbidite sequences were deposited at the EC. Regressive marly deposits (Kimmeridgian and Tithonian) were laid down on both limbs of the DPA. Oxfordian limestones and, on the southwestern limb of the DPA, Triassic and also older soluble rocks, were exposed to karstification. This period was terminated by the universal transgression of Albian-Cenomanian age.

Numerous surface karst landforms are believed to have developed in this period (GILEWSKA, 1964; GRADZIŃSKI and WÓJCIK, 1966). However, most of them are subsided pocket outliers of Mid-Cretaceous transgressive clastics that were created together with removal of Upper Cretaceous deposits during the Tertiary (GRADZIŃSKI, 1962; GŁAZEK, 1973). Probably there were several specific causes for the insignificant extent of karst development during this period: (1) the low relief landscape until the Aptian/Lower Albian times was unfavourable for deep groundwater circulation; (2) the persistence of clayey, impermeable, regressive Upper Jurassic sediments, only slightly weathered at the top beneath the mid-Cretaceous transgression; (3) strong secondary silicification of exposed Upper Jurassic limestones forming gentle hills on the pre-Albian surface in the Cracow-Wieluń Upland (MARCINOWSKI, 1970; GŁAZEK, 1973), and (4) significant uplift and erosion of older rocks occurring only in late Early Cretaceous times, as determined from fission-track cooling-ages (105–95 Ma) of crystalline formations in the Sudetes (JARMOŁOWICZ-SZULC, 1984).

Unequivocal pre-Albian or pre-Cenomanian karst forms are known only in (1) Julianka and Mokrzesz (Cracow-Wieluń Upland); (2) Święta Anna Mount (Silesian Upland), and (3) in the Tatra Mountains (Fig. 2–27).

In Julianka Quarry a hill of completely silicified Upper Oxfordian limestones contains remnants of a cave that developed prior to silicification and submergence beneath mid-Cretaceous clastics. Nearby, in Mokrzesz, MARCINOWSKI (1970) described a pocket filled with silicified limestone debris and covered with Albian-Cenomanian clastics on a similar hill of Oxfordian limestones.

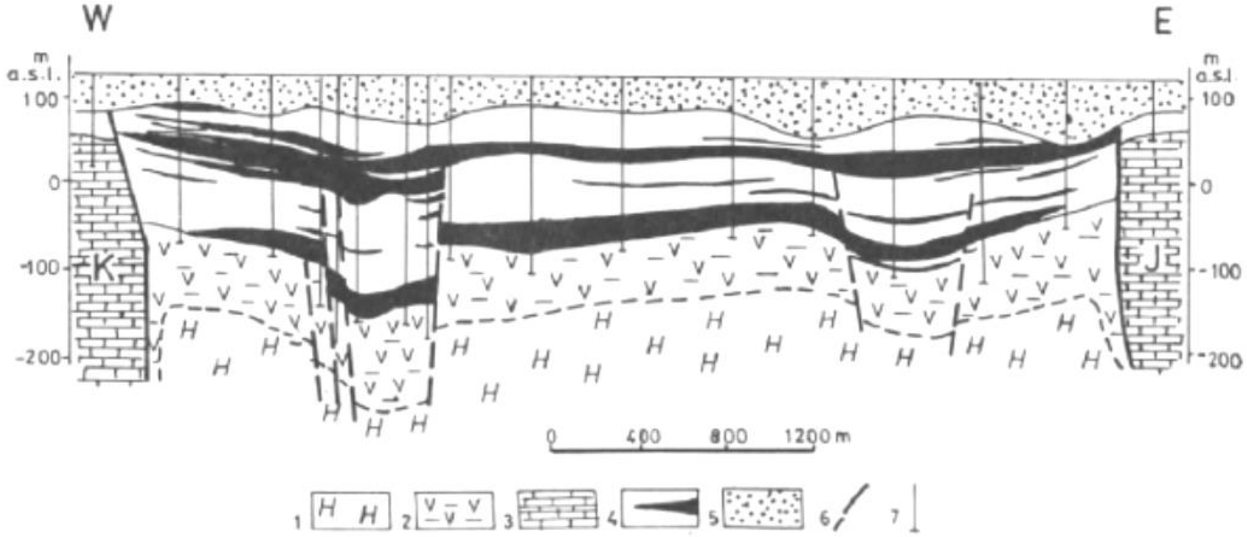
Further to the West, in an old quarry on Święta Anna Mount, the author found a sinkhole filled with grey silts and a layer of limestone boulders bored by lithophages, at the boundary with transgressive clastics. The sinkhole is developed in Middle Triassic limestones.

Traces of pre-Albian syngenetic karstification are known in the High Tatric sequence (PASSENDORFER, 1930; KRAJEWSKI, 1984). At the top of the Urgonian limestones, vadose diagenetic features and minute hollows are known. They are filled with yellow silt that is phosphatized and encrusted with Mn-Fe hydroxides at the top and covered with the condensed pelagic deposits of the Albian.

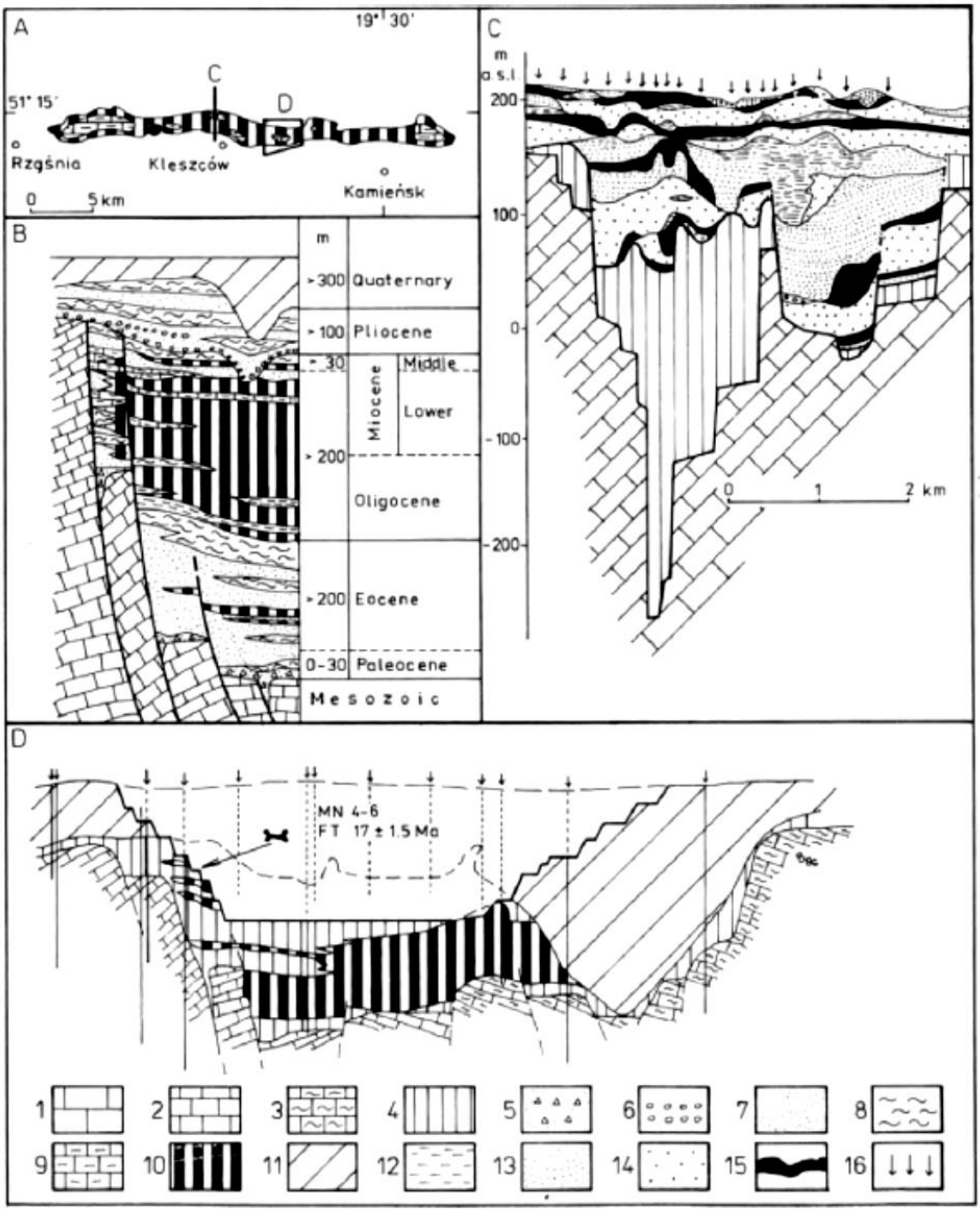
Paleokarst porosity developed in Oxfordian limestones on the slopes of the DPA. This caused catastrophic floods into coal mines being developed in the Lublin Upland in late Seventies. The floods occurred when the shafts reached the Cenomanian-Oxfordian boundary.

There was minor ore mineralization in Oxfordian limestones along some fracture zones in the Silesia-Cracow zinc-lead ore district (BEDNAREK, GÓRECKA and ZAPAŚNIK, 1985). It may be suggested that these ores were derived from underlying Triassic deposits and spread into the limestones beneath Upper Oxfordian marls. The hydraulic head responsible for such deep phreatic circulation was probably caused by uplift of the Sudetic area during Albian times, when Middle Triassic carbonates became exposed.

Thus, during this third period, only one phase (in the late Lower Cretaceous) is well established. It lies in areas relatively far from the DPA subsidence axis. A subtropical, savannah-like climate may be suggested for this phase.



2–30. Section of the Rogóźno brown-coal deposit in a subrosion depression (after CIUK in OSIKA, 1980). 1. top of salt plug; 2. gypsum-clay cap; 3. Mesozoic limestones and marls (J = Upper Jurassic, K = Upper Cretaceous); 4. Paleogene coal-bearing deposits, black = coal seams; 5. Quaternary cover; 6. faults; 7. boreholes.



2-31. Subrosion depression with brown-coal deposits south of Bełchatów, Central Poland. A. Outline-map of deposit (after CIUK and PIWOCKI, 1980) showing distribution of peat and "lacustrine chalk" sedimentation filling the subsidence maxima. Salt dome (black spot) and open-cast mine (contour), as well as section lines (C–D) are marked. B. Stratigraphic scheme of Tertiary deposits (modified after CIUK and PIWOCKI, 1980). C. Section of Quaternary deposits, vertical scale 8 times horizontal (simplified after BARANIECKA and SARNACKA, 1971) showing two periods of maximum subsidence, namely Tertiary (Oligocene-Lower Miocene) and Middle Pleistocene (between two older and two younger glaciations). D. Section through the open-cast mine (after KUSZNERUK, 1984) showing the dated localities, not exaggerated. Mesozoic rocks: 1. undivided, 2. Upper Jurassic

Fourth Period of Karstification; Late Cretaceous – Holocene

The final karstification began with the Upper Cretaceous emergence and has persisted to modern times. However, here it will be treated only until the Middle Pleistocene glaciation, i.e. the Late Pleistocene-Holocene phases or separate Holocene phases if these are discernible are excluded. This long period encompasses many phases that are more or less clearly separated by deposits from marine incursions or from glaciations in the Pleistocene.

The oldest phase is represented by the development of deep subrosion depressions (more than 300 m) in northwestern Poland, along the crest of the Mid-Polish Anticlinorium or to the southwest of its axis (Fig. 2–25). These depressions are filled with Tertiary brown coal formations and are located directly above salt domes (Fig. 2–30; Fig. 2–25 site a) or along fracture zones (Fig. 2–31; Fig. 2–25 site b). In the latter case they are frequently separated from the top of the surviving evaporites by more than 2 km of Mesozoic deposits that display anomalous dips and fracturing.

Some of the depressions, especially those in the north-west, are covered by marine Middle Eocene-Oligocene deposits (Fig. 2–25 site c). They contain Late Paleocene–Early Eocene brown coal formations (CIUK, 1975) and appear to have been inert since at least the Middle Eocene. These depressions mark the first phase of deep intrastratal karst (subrosion). This phase developed as a result of the Laramide elevation of southwestern Poland (FSM, FSB and Sudetes in Fig. 2–25) when Permian clastics and carbonates were exposed by erosion on a sub-Late Eocene surface. Supposedly, groundwater travelled long distances via a combination of older primary (in the clastics) and younger, secondary vadose and diagenetic carbonate porosity (PERYT, 1984) plus Early Cenozoic intrastratal porosity.

No other karst features of this phase are proven. However, many regoliths are ascribed to this time and the Middle Eocene transgression buried an uneven erosional surface. Traces of it were probably later exhumed and incorporated into the younger landscapes, even the Recent one.

A second phase of karstification commenced with the Early Oligocene regression and was caused by considerable uplift of the continental margin facing the Paleogene Tethys Ocean. It was terminated by Middle Miocene (Badenian) transgression from the Carpathian Foredeep. Deep valley patterns were carved at that time and are preserved beneath the Badenian deposits.

The sub-Badenian morphology in the Carpathian Foredeep exceeds 600 m in relief and is recognized as buried valleys extending across the Middle Polish

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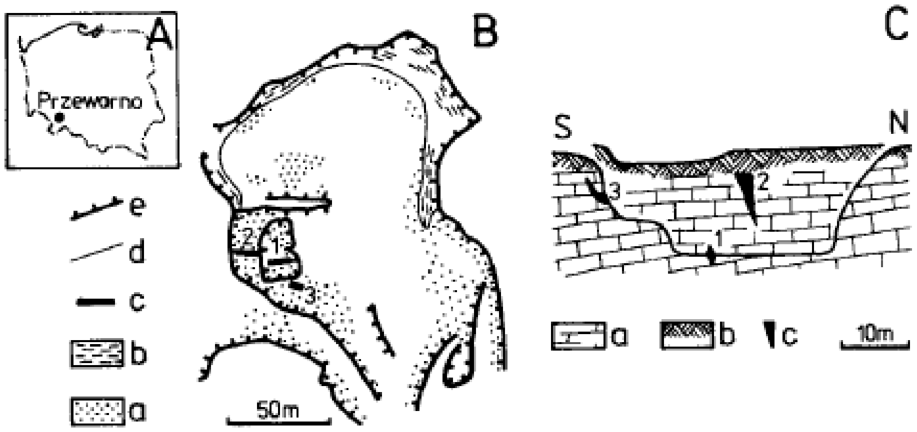
limestones, 3. Upper Cretaceous marls; Tertiary: 4. undivided, 5. weathering rubble waste, 6. gravel, 7. sand, 8. silt and clay, 9. "lacustrine chalk", 10. brown coal; Quaternary: 11. undivided, 12. clay and silt, 13. fine sand, 14. coarse sand, 15. boulder clays and pavements; 16. boreholes.

Uplands from Lower Silesia to the Lublin Upland, as well as in central Poland (STAHL, 1932; RADWAŃSKI, 1969; CZARNIK, 1972; BŁASZAK et al., 1976; PANEK and SZUWARZYŃSKI, 1976; BUŁA and JURA, 1985).

Many surface karst forms developed during this phase (Fig. 2–36) and became fossilized with karst deposits or marine Badenian deposits (GILEWSKA, 1964, 1965; GRADZIŃSKI and WÓJCIK, 1966). Some of them are filled with subsided and decalcified Eocene glauconitic sands (KARASZEWSKI, 1966); many subrosion brown coal-bearing depressions also contain Eocene glauconitic sands at their base (PIWOCKI, 1975). An excellent example of a buried valley and associated group of sinkholes, all filled with local waste and marine Lower Badenian deposits, is described by PANEK and SZUWARZYŃSKI (1976) at the Pb-Zn mine near Cracow (Fig. 2–36 a). This is the evidence that the hydrothermal ore-forming activities were completed before this karstification phase.



2–32. Miocene paleokarst at Przeworno (after GŁAZEK, GALEWSKI and WYSOCZAŃSKI-MINKOWICZ, 1977). A. Location map; B. Sketch-map of the quarry: a. Proterozoic (?) marbles, b. Lower Devonian quartzites and quartz-sericite schists; c. fossil-bearing karst forms; d. geological boundaries; e. escarpments; C. Schematic section through SW part of the quarry: a. marbles, b. Pleistocene deposits and heaps, c. fossil-bearing localities; 1, 2 and 3, i.e. Przeworno 1, Przeworno 2 and Przeworno 3.

The most prominent assemblage of paleokarst forms of this phase was discovered at Przeworno (GŁAZEK, OBERC and SULIMSKI, 1971; GALEWSKI and GŁAZEK, 1973; Figs. 2–32 and 2–36) in an isolated marble hill surrounded by Middle Miocene alluvial plain deposits. Three sites are known here:

(1) The oldest (?), Przeworno 1, is a horizontal karst channel filled with grey kaolinitic-illitic clays containing dispersed vertebrate bones and teeth transported by water. The presence of *Conohyus simorrensis* (LARTET) points to the Badenian (KUBIAK, 1982). According to MEIN'S (1976) Neogene mammalian zonation (abbr. MN) it belongs to zones MN 5-6 (GŁAZEK and SZYNKIEWICZ, 1987).

(2) Przeworno 2 is a vertical fissure filled with illitic clay containing marble blocks and vertebrate remains slightly cemented with amorphous silica. Occur-

2–33. Middle Miocene siliceous flowstone in the cave floor of site Przeworno 3, coin diameter 3 cm (Photo by J. Głazek).

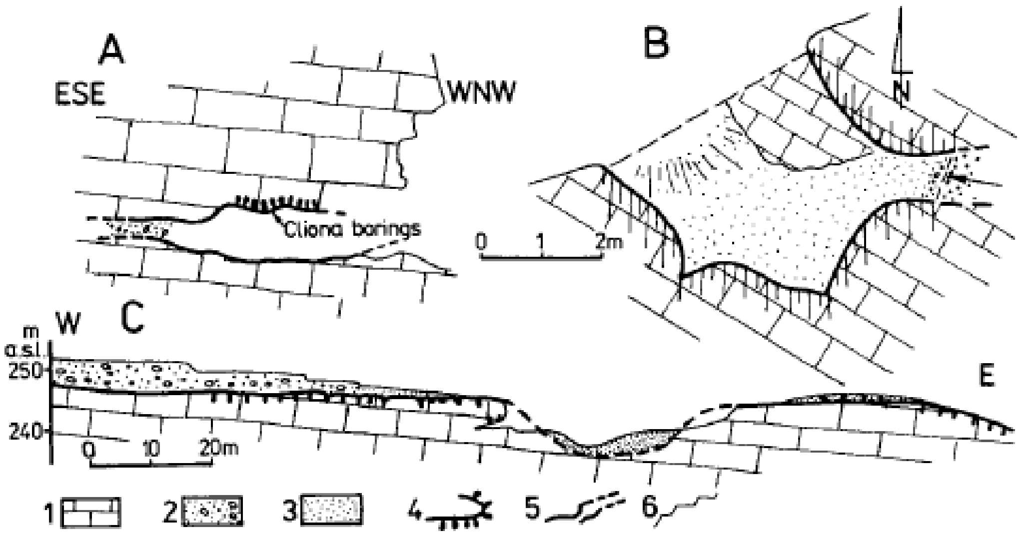
2–34. Middle Miocene diving beetle *Acilius cf. sulcatus* (L.) in the siliceous flowstone from the site Przeworno 3, x4 (Photo by B. Drozd).

rence of *Pliopithecus antiquus* (BLAINVILLE) and *Conohyus simorrensis* (LARTET) points to zone MN 6 (GŁAZEK and SZYNKIEWICZ, 1987).

(3) Przeworno 3 is a steep cave filled with siliceous flowstones (Fig. 2–33) containing diving beetles (Fig. 2–34), fishes, dragon-fly larvae and green algae.

These exceptional deposits were covered with laminated clays containing Middle Miocene pollen (GALEWSKI and GŁAZEK, 1973, 1978; GŁAZEK, GALEWSKI and WYSOCZAŃSKI-MINKOWICZ, 1977; SADOWSKA, 1977). The cave was probably a sinkhole draining the marshy surface of a Middle Miocene alluvial plain on which alkaline volcanic waters rich in silica became mixed with acid peat waters that carried the faunal remains; note the silicified mould inside a beetle carapace and the missing extremities (Fig. 2–34)

The Lower Badenian transgression onto the southern slope of the Holy Cross Mountains covered a diversified morphology and created Dalmatian type of shore line there for a short time (RADWAŃSKI, 1969). A small littoral cave is preserved and was exhumed at Lubania (GŁAZEK and RADWAŃSKI, 1970; Fig. 2–35).

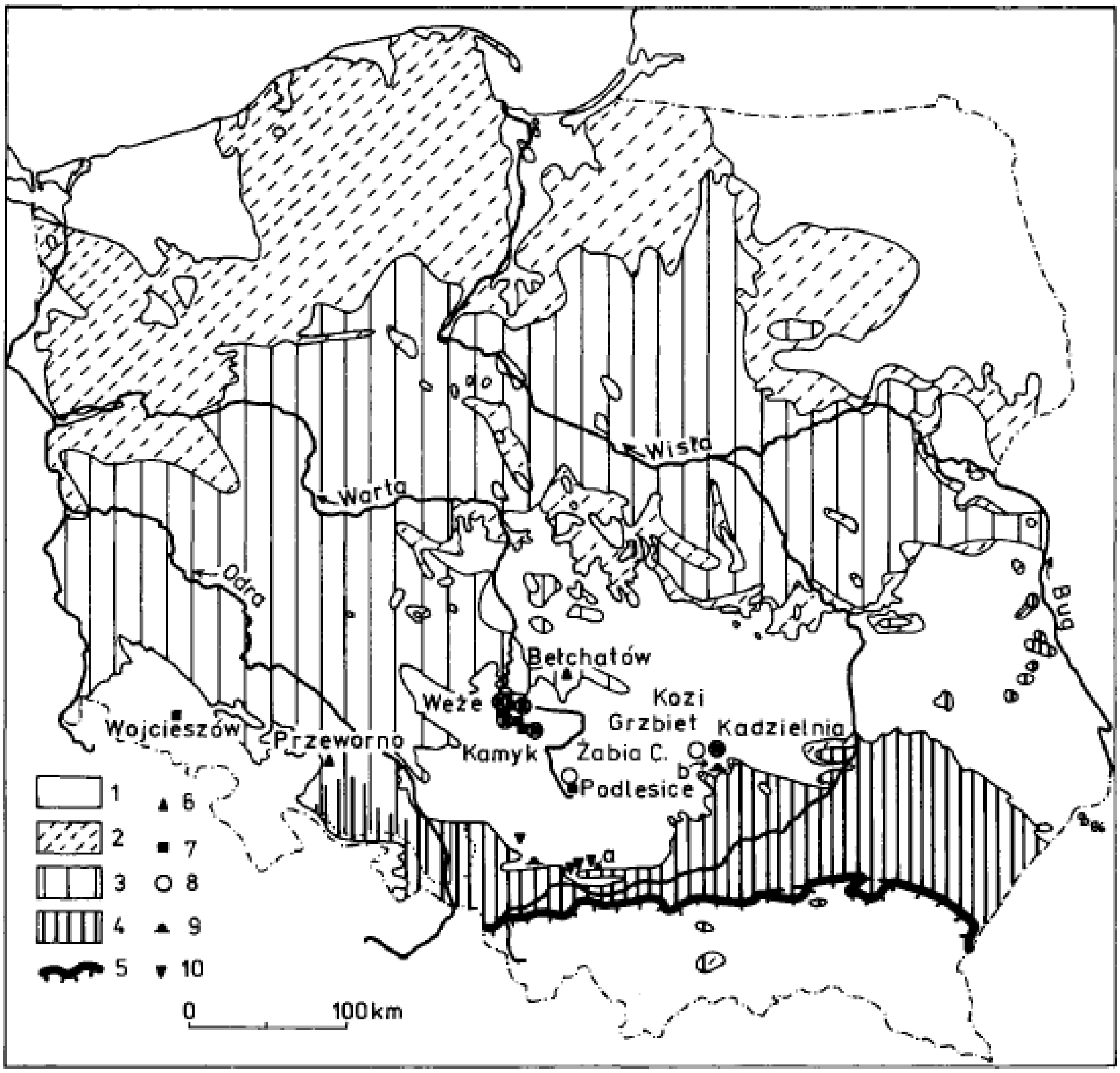


2–35. Littoral cave of Early Badenian age at Lubania on the southern slope of Holy Cross Mountains (cf. Fig. 2–36.; after GŁAZEK and RADWAŃSKI, 1970). A. Section; B. Plan (arrow marks section line); C. Geological section 1. Oxfordian limestones, 2. Badenian lithothamnian limestones, 3. Quaternary alluvial deposits, 4. Badenian borings on the abraded Oxfordian limestones; surfaces of limestones: 5. original, 6. secondary (due to subsequent erosion or excavation).

Numerous subrosion depressions filled with brown coal deposits of Oligocene and Lower Miocene age are associated with this pre-Badenian morphology (Fig. 2–25). The depressions were created or reactivated shortly after uplift as a consequence of groundwater flow down-dip via older paleokarst porosity with newly developed intrastratal porosity.

This situation is well illustrated and was recently dated in Bełchatów Coal Mine (Fig. 2–31). At the top of the coal measures were two layers of tephra intercalated with "lacustrine chalk" and a thin uppermost coal seam. The tephras were dated by the fission-track method by J. BURCHART (pers. comm., 1985) and by micromammals extracted from the "chalk" studied by V. FAHLBUSCH (pers. comm., 1985; BURCHART et al., in prep.). The age is approx. 17 ± 1.5 Ma (MN zones 4-6?). Together with numerous occurrences of Badenian foraminifera in clays overlying the coal-bearing deposits or erosional features (ŁUCZKOWSKA and DYJOR, 1971), that fixes the age of the upper boundary of this karstification phase (Fig. 2–36).

Borehole and speleological explorations in the Cracow-Wieluń Upland show



2–36. Neogene paleokarst localities in relation to contemporaneous deposits. 1. pre-Neogene rocks, 2. Oligocene-Lower Miocene fluviatile brown coal-bearing deposits of subsided continental margin, 3. alluvial-coastal plain deposits of Middle Miocene, 4. marine Middle Miocene of Carpathian Foredeep, 5. frontal overthrust of Carpathian nappes; fossiliferous karst localities: 6. Badenian, 7. Pliocene, 8. Lower Pleistocene, 9. remnants of caves buried by Badenian marine deposits, 10. sinkholes buried by Miocene deposits; a. Zn – Pb mine at Chrzanów, b. littoral cave at Lubania.

that karst water circulation was well organized in this phase up to the base of the Upper Jurassic limestones (i.e. over 300 m below surface and over 100 m b.s.l.); sinkholes filled with variegated siliciclastics exceed 100 m in depth and vertical caves display 50 m of relief. All these cavities, surface depressions and nearly all morphology of the Middle Polish Uplands were then filled with fine-grained clastics and covered with marine to alluvial plain deposits in Middle Miocene times (DŻUŁYŃSKI et al., 1966; GŁAZEK and SZYNKIEWICZ, 1987).

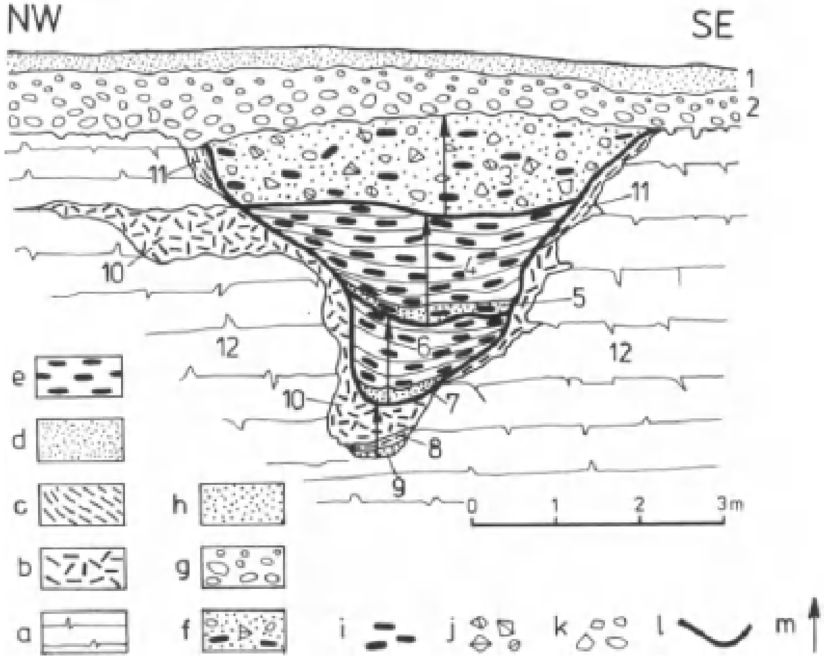
There is no site among the one hundred already known that contains vertebrate remains belonging to zones, MN 8–13, i.e. Upper Sarmatian-Pontian (GŁAZEK and SZYNKIEWICZ, 1987).

The third karst phase followed erosion of the Middle Miocene overburden as a result of the Messinian crisis and Pliocene uplift. Numerous exhumed caves reveal complicated sequences of bone-bearing deposits from Lower Pliocene to Early Pleistocene age (MN 14-17 and Q 1-2). Lengthy investigations of material excavated by J. Samsonowicz demonstrate the cyclic climatic changes that occurred in the Pliocene and Early Pleistocene (Fig. 2–37) before continental glaciations reached the Mid-Polish Uplands (SAMSONOWICZ, 1934; SULIMSKI, 1964; GŁAZEK, SULIMSKI and WYSOCZAŃSKI-MINKOWICZ, 1975).

Numerous karst features in the uplands are filled with red deposits and contain similar vertebrate faunas of Ruscinian (MN 14-15), Villányian (MN 16-17) or Biharian (Q 1-2) age, but in lesser quantities and in one or two layers (cf. Fig. 2–36).

Sulphur deposits in the northern slope of the Carpathian Foredeep also belong to this phase of karstification. A Middle Badenian gypsum was altered into cavernous marls in which the secondary porosity is partly filled with sulphur. This alteration is restricted to zones where the gypsum is below present river levels and covered by Middle Miocene clays 10–180 m thick. The sulphur was concentrated and preserved in a sequence of three distinct steps: (1) reduction of the original gypsum to H_2S by bitumens carried by groundwaters; (2) oxidation of H_2S to S by aqueous oxygen supplied in limited quantity or for a very short time, and (3) invasion by phreatic stagnant waters, which excluded the further oxidation of sulphur to gypsum (OSMÓLSKI, 1976). These steps can be interpreted as follows: (1) initial reduction to the Late Miocene, when the overthrust of the Carpathians onto Middle Miocene deposits expelled connate waters containing bitumens northwards into the shallow zone of the foredeep where the gypsum is interbedded with clastics and limestones; (2) slight oxidation to the Messinian entrenchment of rivers along the northern part of the foredeep, which reversed the direction of groundwater flow in its shallow parts via pre-existing paleokarst porosity, and (3) restoration of phreatic conditions to the Pliocene, when the joint effects of refilling the Black Sea Basin and the uplift of the Carpathian Foredeep halted the flow of fore-Carpathian rivers to the Black Sea.

The ensuing Pleistocene glacial epoch is characterized by short duration changes in the conditions of karst development. Each glaciation abruptly fossilized older karst forms or excavated them, depending upon the contemporaneous and local dynamics of water circulation. There is insufficient evidence

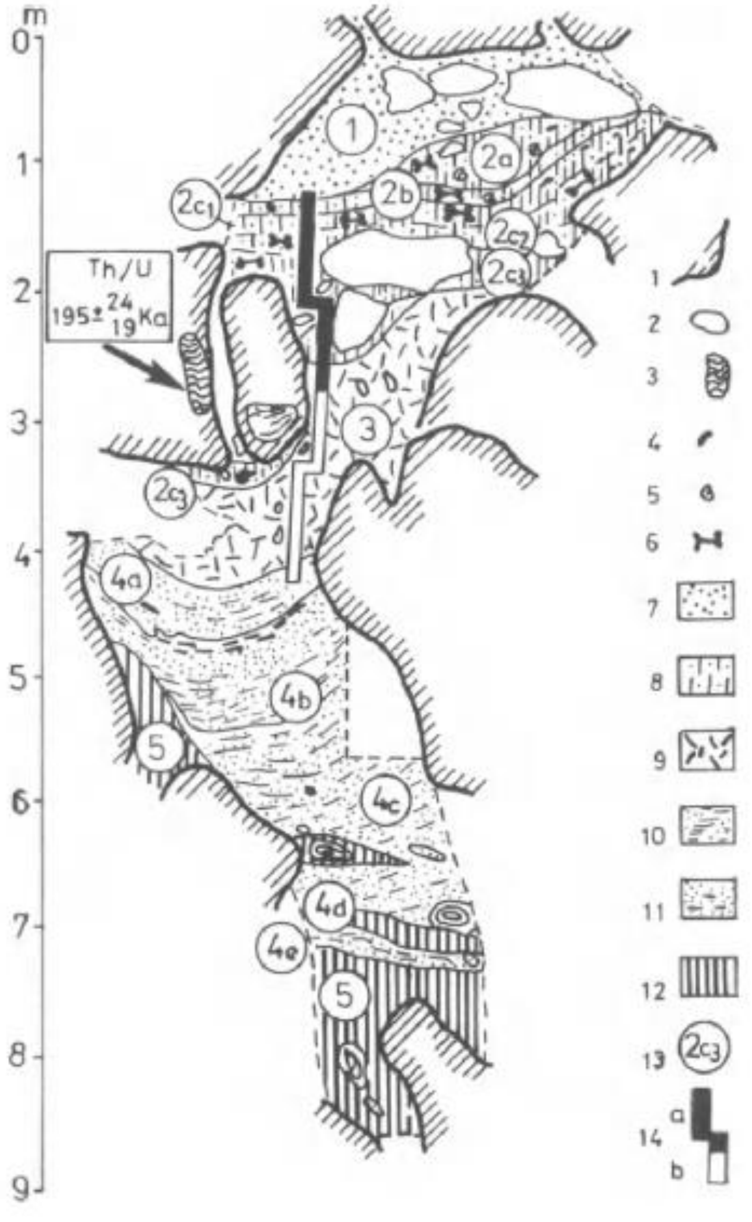


2–37. Cross-section of the Węże 1 site (modified after SAMSONOWICZ, 1934, and GŁAZEK, SULIMSKI and WYSOCZAŃSKI-MINKOWICZ, 1975). 1–12. Samsonowicz's bed numbering; a. Oxfordian limestones (12), b. stratified flowstone calcite (10), c. pink flowstone (8, 11), d. red calcareous sandstone (5, 7, 9), e. grey bone-bearing flowstone (4, 6), f. pink breccia with blocks of Oxfordian limestones and grey bone breccia (3), g. periglacial cover of rock debris (2), h. sandy soils (1), i. bones, j. blocks of grey bone-bearing flowstone, k. blocks of Oxfordian limestones, l. erosional boundaries of sedimentary cycles in cave deposits, m. subsequent cycles of cave deposits.

for reasonably accurate correlation between karst and glacial events or to distinguish which karst phases represent particular interglacials. However, there are enough data to show that some spectacular changes in karst processes were caused by glaciations, as well as evidence in the karst that contributes significantly to our knowledge of the glacial events that occurred in Poland.

The karst relief and karst groundwater circulation were mostly fossilized during the glaciations. However, there were some prominent effects of meltwater attack and/or interglacial karstification.

The oldest glaciation recognized in cave deposits at Kozi Grzbiet (Figs. 2–36 and 2–38) belongs to the Upper Biharian in the European mammalian stratigraphy and to the lowermost Brunhes paleomagnetic epoch (GŁAZEK, LINDNER and WYSOCZAŃSKI-MINKOWICZ, 1976; GŁAZEK et al., 1977; BOSÁK et al., 1982). The first ice sheet reaching that particular area substantially changed the

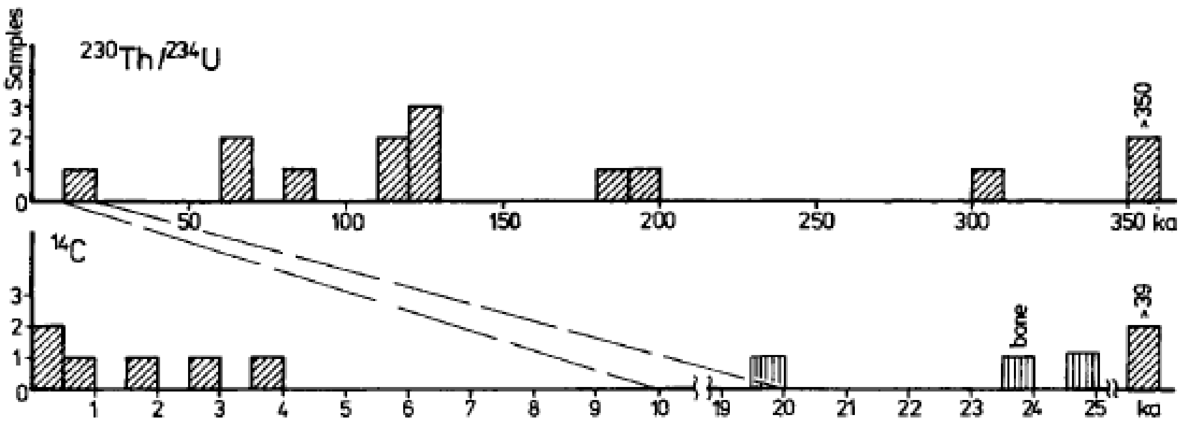


2–38. Geological section of the Kozi Grzbiet site (modified after GŁAZEK, LINDNER and WYSOCZAŃSKI-MINKOWICZ, 1976). 1. Devonian limestones, 2. boulders of the former within cave sediments, 3. flowstones (Th/U dated piece is marked, cf. GŁAZEK and HARMON, 1981), 4. older flowstone debris, 5. snails, 6. bones, 7. outwash sands of Sanian glaciation, 8. brown fossil-bearing cave loams, 9. brecciated cherry-red clays, 10. red sandy clays, 11. red sands with cherry-red clay streaks, 12. brownish clays with carbonate concretions, 13. lithostratigraphic units described in detail by GŁAZEK, LINDNER and WYSOCZAŃSKI-MINKOWICZ (1976), 14. paleomagnetic column (cf. GŁAZEK et al., 1977): a. normal magnetization (Brunhes epoch), b. reversed (Matuyama?). Note: beneath the material fossilizing the cave, which consists of fluvioglacial sands accompanied by frost-shattered limestone blocks (Unit 1), there are interglacial fauna-bearing layers (Unit 2) with marked climatic fluctuations (the warmer phases are 2b and $2c_2$) which contain Scandinavian material. Frost-shattering is visible as limestone blocks in the base of Unit 2 (layer $2c_3$) and brecciation of red clays (Unit 3). Units 3–5 represent Pliocene (?) filling of a vertical cave of Messinian or pre- Badenian age.

composition of local clastic deposits as a result of the admixture of Scandinavian material derived from crystalline rocks. It serves as a prominent bench-mark in the differentiation of Pleistocene and Pliocene karst fillings. The other bench-mark is the common red colour caused by hematite in the Pliocene fillings, while a brown colour caused by goethite characterizes the Pleistocene fills.

After two continental glaciations marked by boulder clays, strong subrosion activity caused parallel subsidence along the northern side of the Bełchatów brown coal deposit (Fig. 2–31 C). The subsidence was active before the last three glaciations (two of which covered this area but the last, the Vistulian, did not extend so far). This structure, when discovered, was first interpreted as an "interglacial valley", then as evidence of an "endogene tectonic phase" during the Middle Pleistocene interglacial! Similar "grabens" (deeper than 100 m) are found on salt domes in central Poland. They display an effect of glacial deep water circulation systems that follow paleokarst paths.

Creative action by glacial meltwater is represented by the development of Szachownica Cave in the northern part of the Cracow-Wieluń Upland (GŁAZEK, RUDNICKI and SZYNKIEWICZ, 1977; GŁAZEK et al., 1979). This cave system has a total passage length of more than one kilometre. It developed in a fracture net during the melt of the Wartanian glacier on the top of a limestone



2–39. Isotope dating of speleothems and bones from caves of Poland. Uranium series dating of speleothems from all karst areas (after GŁAZEK and HARMON, 1981, in print) show discontinuous Pleistocene speleothem precipitation. Radiocarbon dating of flowstones and bones from the Magura Cave, Tatra Mountains (after HERCMAN et al., 1987) shows the last glacial non-deposition between 11 and 23 Ka.

hill that was nearly completely buried beneath outwash sands. The cave was fossil during the Upper Pleistocene and Holocene.

Available results of speleothem dating (Fig. 2–39) from caves scattered throughout the Polish karst areas (GŁAZEK and HARMON, 1981, in press; T. C.

ATKINSON, pers. comm., 1985) show discontinuous speleothem deposition and some temporal constraints on the development of the karst landscape, as well as suggesting timing of glacial events.

Spacious caves of the Cracow Upland that were thoroughly studied for archeological purposes (MADEYSKA, 1969, 1981, 1982) have revealed major episodes of excavation in the Pleistocene. These caves of supposedly Middle Miocene age contain only remnants of red allochthonous sediments of the Pliocene in vadose entrenchments, and huge Upper Pleistocene deposits. The latter were dated by the ^{14}C technique to 38 160 $\pm$ 1 250 y B.P. (GrN 2181) and contain broken stalagmites dated by the $^{230}Th/^{234}U$ technique to 110–130 ka (GŁAZEK and HARMON, 1981, in press).

The Pleistocene glaciations in the High Tatra Mountains caused numerous changes in the hydrologic environments of caves but only a few of these changes are dated and correlated with glacial events. However, available speleothem and bone dating (GŁAZEK and HARMON, 1981; GŁAZEK, 1984; HERCMAN et al., 1987; RÓŻAŃSKI, pers. comm., 1985) sedimentological data (WÓJCIK, 1966), and speleological reconstructions (RUDNICKI, 1967; GŁAZEK, RUDNICKI and SZYNKIEWICZ, 1977) reveal that: (1) the last (and most severe) glaciation in these mountains took place between 11 and 23 ka (cf. Fig. 2–39); (2) since speleothems older than this glaciation occur in active caves near valley bottoms and speleothems older than 300 ka occur approx. 40 m above the valley bottoms, these horizontal caves are considerably older than was expected and the glacial entrenchment of the valleys is considerably less than was supposed; (3) stagnant glacial water filled many high-lying, older caves (up to 200 m above the valley bottom); (4) many vertical caves were developed through older horizontal caves as a result of the drainage of stagnant and proglacial waters.

Last but not least, because the Tatra crystalline rocks have fission-track cooling-ages of approx. 15 Ma it seems that the general erosional dissection of the mountains was of Messinian and Pliocene age, while the glacial Pleistocene was only responsible for minor landscape modification of the already dissected mountains!

Paleogeographic conditions were highly variable during this last, long karst period. Wet and mildly moderate, passing into subtropical climates may be suggested for the first phase (Paleocene to Lower Eocene). The next karst phase (Oligocene to Lower Miocene) began with a strong deterioration of the climate (BUCHART, 1978; CAVELIER et al., 1981). Probably it was a wet, moderate climate gradually passing in the Early Miocene into mild subtropical conditions. Both Tertiary climatic optima (Middle Eocene and Middle Miocene) coincide with marine transgressions and so were not important for karstification in Poland.

The third karstification phase began in Late Miocene times with considerable drying and fall of temperature. The climate was continental, even semi-arid, during the Messinian as is shown by the presence of typical inhabitants of the African desert margins (*Gerbillinae, Hystrix*) in the lowermost Pliocene faunas (MN 14, e.g. Węże 1 and Podlesice sites, KOWALSKI, 1974; SULIMSKI, 1960). It was the Messinian dessication and the rise of the Alpine-Carpathian barrier that together created markedly continental climates throughout the whole of Europe, with the introduction of African and Asiatic semi-desert and steppe micromammal fauna. They dominate in the bone-bearing Pliocene karst sites of Poland (GŁAZEK and SZYNKIEWICZ, 1987).

The last karstification phase is characterized by strongly alternating climates, moderate in interglacials and cold in glacials.

Practical Consequences

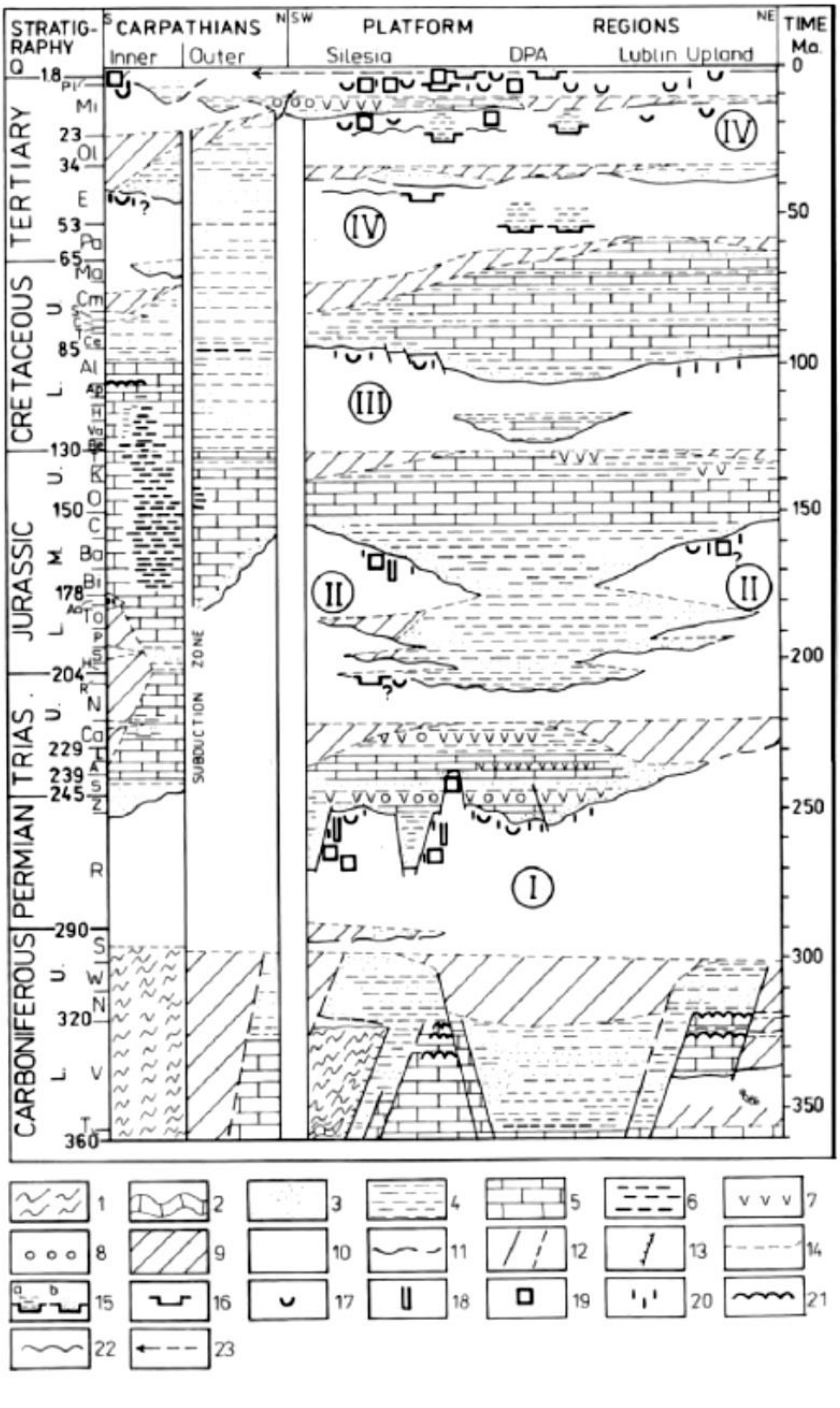
Many important mineral deposits in Poland are associated with the operation of paleokarst processes. Hydrothermal karst of Mesozoic age is responsible for the most important zinc-lead deposits in the Cracow-Silesia ore district. These are discussed by DŻUŁYŃSKI and SASS-GUSTKIEWICZ, p. 377–397.

Important sulphur deposits in the Carpathian Foredeep were developed by paleokarst water circulation during the Neogene. Most of the brown coal deposits in Poland were also associated with paleokarst intrastratal dissolution of Permian evaporites. These deposits filled subrosion subsidences that resulted from deep regional groundwater circulation conveyed principally within the paleokarst porosity of the Zechstein carbonates.

Some small oil and gas deposits have been found in karstified Oxfordian limestones. These limestones form buried "hills" beneath Badenian deposits in the Carpathian Foredeep. Other minor deposits of oil and gas are found in the Zechstein carbonates in the Polish Lowland. The oil accumulated in secondary porosity that developed as a result of syngenetic and post-diagenetic paleokarst.

Many small deposits of lead, copper and iron ores were exploited over the centuries in karstified Devonian carbonate host-rocks in the Holy Cross Mountains (RUBINOWSKI, 1971). Numerous deposits of clays, moulding sands and iron ores were or are still exploited in karst depressions of Tertiary age in different regions of Poland (BOSÁK et al., 1979).

Some catastrophic subterranean floods have been caused by long distance groundwater systems flowing through paleokarst cavities in: (1) Lower Silesian copper mines (KRASOŃ and WÓJCIK, 1965); (2) the coal mines of the Lublin Upland, and (3) the zinc-lead mines in Cracow-Silesia ore district (see WILK, p. 513–531) and many open-cast mines and quarries.



2–40. Time distribution of paleokarst phenomena and sediments in Poland. Metamorphosed basement: 1. silicate rocks; 2. marble lenses; Sedimentary rocks: 3. psammites and psephites; 4. silts-clays (including marls); 5 – carbonates; 6 – deep sea carbonate-silicates; 7 – sulphates; 8 – salts; 9 – unknown deposits stripped by erosion; 10 – subaerial degradation; Boundaries: 11 – unconform-

Conclusion

Paleokarst is a rich and complex phenomenon in Poland. Its study has a long tradition and is of growing importance. The most striking paleokarst in this country developed in post-Variscan (until Middle Triassic) and in Tertiary times. The distribution of paleokarst phenomena in the geological past and in geographic space is shown in Figs. 2–25, 2–27, 2–36 and 2–40.

able cover; 12 – synsedimentary faults; 13 – synsedimentary overthrusts; 14 – supposed limits of sedimentation; 15 – subrosion depressions filled with contemporaneous deposits (a. brown coal – bearing, b. drift deposits); 16 – poljes; 17 – sinkholes; 18 – shafts; 19 – caves; 20 – minor solution forms; 21 – syngenetic karst; 22 – karst corrosion surfaces; 23 – maximal extent of Pleistocene glaciers (Scandinavian ice-sheet in platform regions); I, II, III and IV are periods of karstification; time scale according to ODIN (1982).