Int. J. Speleol. 24 (Phys.), 1-4 (1995): 3-39

PALEOKARST OF THE BOHEMIAN MASSIF IN THE CZECH REPUBLIC: AN OVERVIEW AND SYNTHESIS

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ABSTRACT

Paleokarst of the Bohemian Massif on the territory of the Czech Republic developed as polygenetic and polycyclic forms with several phases of fossilization and rejuvenation depending on tectonic phases and deep chemical weathering. Paleotectonic period (pre-Permian in general) was characterized by evolution of relatively minor depositional and local paleokarsts. Neotectonic (platform) period (post-Permian) favoured the prolonged karst evolution of interregional paleokarst in two karst periods and several more or less distinctly separated karst phases.

INTRODUCTION

The Bohemian Massif is sometimes called also the "*roof of Europe*" noting its elevated tendecy since its consolidation during the Variscan Orogeny. The region is known by landforms that have been intricately and unequally developed during many periods and phases of changing climate and of tectonic activity in the geological past. This very complex form of the karst and paleokarst, with relict, fossil, recent, active or rejuvenated features and in periglacial conditions transformed karst, led Panos (1964) to define it as the *Central European Type of polycyclic karst*. The polycyclic and polygenetic nature of karsts and paleokarsts represents the specific characteristics for karst evolution of the whole Bohemian Massif, and leads to the presence of polycyclic and polygenetic features attributed to paleokarst also within the present landscape. They sometimes form a great part of present objects of the speleological interest. To distinguish what is ancient and what can be remodeled at the present time is therefore very difficult. This fact is also reflected in terminological problems.

Karst areas, measured on outcrops of carbonate rocks, in the Bohemian Massif total only nearly 300 km^2. The largest karst region in the Moravian Karst with about 85 km^2 (fig. 1). The rest of karst rocks occur as small outcrops, lenses and/or tectonic blocs or strips in highly folded regions forming so-called scattered (isolated) type of karst. Allogenic karst regions dominate, surrounded by siliciclastics and/or metamorphic or plutonic sequences. The scattered type of karst highly influenced the polycyclic and polygenetic nature of paleokarsts and it is typical feature of the Massif. Karst areas which now form subcrops, sometimes buried several thousands of metres, occured in erosional section on the surface in the past as proved by paleokarsts from drilling. They occupy area which can be roughly estimated to about 800-1 000 km^2 for Devonian to lower Carboniferous carbonates and about 1 000 km^2 for upper Jurassic limestones (fig. 1).

The general review of paleokarsts of the Bohemian Massif was presented by Bosák,

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Horácek and Panos (1989). Individual karst regions were summarized also by Panos (1962, 1964, 1965), Bosák and Horácek (1981), Bosák (1985, 1990c), and Dvorák *et al.* (1993). Nevertheless, the interest in paleokarsts has a long-lasting tradition starting with studies of André (1821) and Reichenbach (1834) in the Moravian Karst.

THE GEOLOGICAL BACKROUND

The complexity of paleokarst evolution resulted from the geological history of the Bohemian Massif, especially from the dominance of nondeposition in the platform stage. The Bohemian Massif represents the epi-Variscan platform consisting of two major

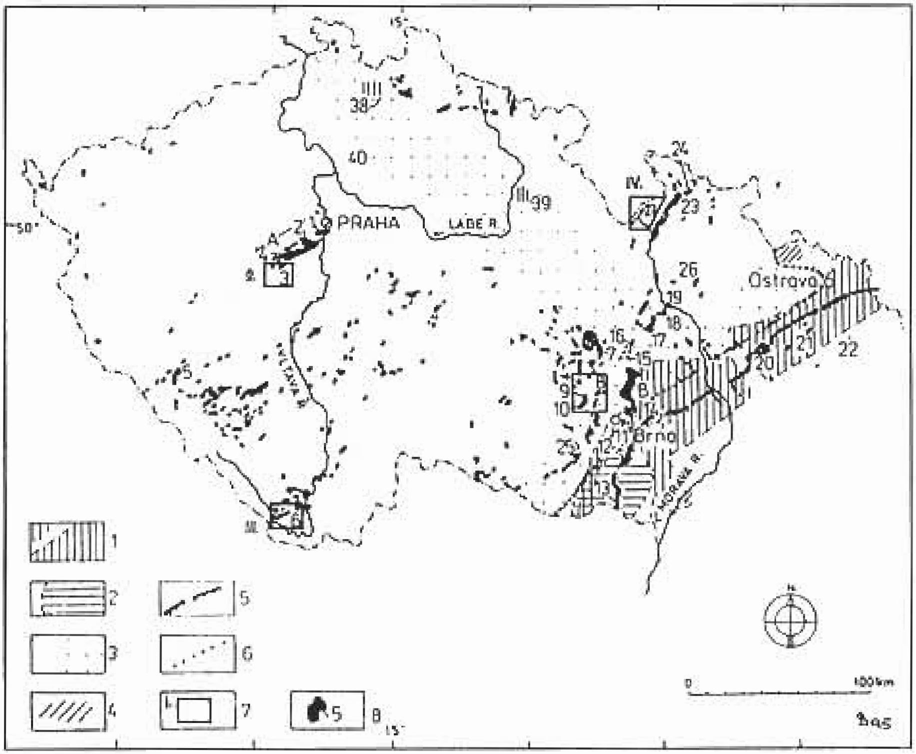

Fig. 1 - Karst areas in the Czech Republic (modified from Bosák, Horácek and Panos 1989)

1, subcrops of Devonian to lower Carboniferous carbonate rocks, 2. subcrops of upper Jurassic carbonate rocks, 3. hypothetical extent of the upper Jurassic sea strait, 4. Miocene (Badenian -Wieliczkian) gypsum, 5. boundary of the Outer Carpathians, 6. western boundary of Miocene Carpathian Foredeep, 7. selected case studies (I. the Tisnov Karst, II. the Koneprusy area, III. the Václav Mine at Blizná, IV. Horní Morava), 8. karst areas (A. the Bohemian Karst, B. the Moravian Karst, 1.-4. the Bohemian Karst: 1. the Dívcí hrady Hill in Praha, 2. Zadní Kopanina at Praha, 3. the Koneprusy area, 4. the Paraple Quarry at Svaty Jan pod Skalou, 5. Loreta at Klatovy, 6. Blizná, 7.-10. the Tisnov Karst: 7. Kunstát and Olesnice, 8. Cebín and Malhostovice, 9. the Kvetnice Hill, 10. Heroltice-Lazánky-Marsov, 11. Stránská Skála and Svédské sance south of Brno, 12. the Carpathian Foredeep - south (the Menin borehole), 13. the Turold Hill at Mikulov, 14. the Carpathian Foredeep - centre (the Svábenice borehole), 15. Nemcice, 16. Vratíkov, 17. Hvozdecko and Javoricko, 18. Mladec and the Tresín Hill, 19. Cervenka at Litovel, 20. the Hranice Karst, 21. the Kotouc Hill in Stramberk, 22. the Ostrava region (boreholes at Krásná), 23. Branná and Vápenná, 24. Supíkovice, 25. Moravsky Krumlov, 26. Sovinec, 27. Horní Morava, 38. the Stáz block at Ceská Lípa, 39. Nepasice at Hradec Králové, 40. the Mseno Carboniferous Basin.

blocks, i.e. the Bohemian Massif proper in the west and partly subducted promontory of the East European Platform -Brunovistulicum (Dudek 1980) - in the east. Brunovistulicum represents the oldest element in the structure of the Massif (more than 1.3 ba). The eastern and southeastern slopes of the Massif are covered by the Carpathians as a consequence of Alpine nappe overthrusting over the epi-Variscan platform in the foreland of Alpine - Carpathian chain (Grecula and Roth 1978)

Three structural levels can be distinguished in the Massif (e.g. Suk *et al.* 1984): (1) Precambrian (Cadomian) basement composed dominantly of metamorphites and plutonites. Crystalline limestones and dolostones occur within the Varied Group of the Moldanubicum; (2) Variscan (Paleozoic) level with development of sedimentary and sedimentary-volcanic sequences, dominantly of marine origin, in places metamorphosed and intruded by plutonites. Carbonate rocks of upper Silurian (Pridolian) to middle Devonian (Eifelian) are known from the Barrandian area and from South Bohemia, Middle Devonian (Eifelian) to Lower Carboniferous (Tournaisian) occur in Moravia and in North Bohemia, and (3) Platform (post-Variscan) level composed dominantly of sediments (continental and marine) separated by important unconformities. Upper Jurassic limestones and dolostones (Callovian to upper Tithonian) cover eastern margins of the Massif. Some upper Tertiary carbonates and evaporites (Karpatian and Badenian) are developed in Moravia (fig. 1). No paleokarst developed during the formation of the Cadomian basement. The Variscan level is characterized by abundant evolution of many small paleokarst horizons. The Platform level is characterized by the broad and intensive paleokarst evolution (fig. 2).

Post-Variscan platform evolution since upper Permian or lower Triassic can be assigned to the *neotectonic period* of evolution, while Precambrian and Variscan levels correspond to paleotectonic period. The *paleotectonic period*, prior to the consolidation of the epi-Variscan platform, is characterized by high mobility and resulted in a great changes in facies development. The neotectonic period is more quiet with only several important marine transgressions covering larger extent of the Massif (upper Jurassic, Cenomanian, middle Miocene). The evolution of eastern and southeastern margins of the Massif (majority of Brunovistulicum) facing the Tethys realm as passive continetal margins was especially strongly influenced by the Alpine Orogeny as being submerged under thick pile of flysh nappes and molasse deposits.

The influence of single phases of Alpine Orogeny to paleogeography and tectonics of the Bohemian Massif has been summarized by Malkovsky (1979) and Roth (1980). They influenced to a great extent also the course of individual karstification phases (*cf.* fig. 2) bringing the energy to the karst/relief system.

NOTES TO TERMINOLOGY

The terminological problems appeared as the reflectance of the complexity of the problem in our geological and geomorphological environment. A lot of ancient karst forms occur within recently active karst structures and they are still or newly developing. Therefore *paleokarst* is refered to karst developed largely or entirely during past geological periods (Bosák, Ford and Glazek 1989) by agents active in karst environment in the past (Laznicka 1985) under morphogenetic conditions differing from the present (Gams 1973, Panos 1978). As the *fossil karst* we can mention only karst forms which completely originated in the past, entirely fossilized and loosing its hydrological characteristics without any traces of present developement; such forms were designated as fossil karst *s.s.* (e.g. Panos 1978). Fossil karst *s.l.* is characterised by polycyclic origin with more phases of development, fossilization, rejuvenation, including also relict karst landforms (Bosák, Horácek and Panos 1989) and it is equal to our meaning of the paleokarst. This broader meaning will be used also hereafter including both relict paleokarst (present landscapes formed in the past) and buried/covered paleokarst (karst landscape buried by sediments) comparably to Choquette and James (1988). Definitions of individual categories of paleokarsts can be found mentioned in very similar way in many sources (e.g. Monroe 1970; Jennings 1971, 1985; Gvozdetsky 1972; Quinlan 1972; Sweeting 1972; Walkden 1974; Panos 1978; Tsykin 1980; Wright 1982; James and Choquette 1988; Bosák *et al.* 1989; Ford and Williams 1989).

The great achievements have been made by sedimentologists studying diagenetical changes of carbonates connected with freswater and marine diagenetic stages. Karst and paleokarst started to be treated as a diagenetic facies (Esteban and Klappa 1983) or subacrial diagenetic terrane (Roehl 1967). A lot of early paleokarsts developing in the evolution of carbonate depocentres really represent results of freshwater diagenetic facies and led Esteban (1991) to distinguish two models of paleokarstification -i.e. the Carribean and the general models. The study of the former is based on the sequences of diagenetic facies characterizing karstification equivalent to the depositional or local paleokarst types (syndepositional with carbonate sequences), the latter is equivalent to conditions of long-lasting subaerial exposure far from marine domain (interregional paleokarsts *sensu* Choquette and James 1988). This approach influenced the paleokarstology as the individual scientific discipline especially in past ten years (*cf.* Wright, Esteban and Smart 1991, Choquette and James 1988) using abundant data from petroleum and mineral deposit exploration in carbonates.

STRATIGRAPHY OF PALEOKARST

Combination of sedimentological/diagenetic approach with seismic and sequence stratigraphy, new ideas on paleokarst stratigraphy appeared. Karstification periods and karstification phases (Herak and Stringfield 1972; Glazek 1973; Bosák 1981b; Bosák, Ford and Glazek 1989) and their equivalents of interregional and local paleokarsts together with the depositional paleokarst (short karst episodes) (Choquette and James 1988) were defined in the past. The use terminology of Choquette and James (1988) seems to be with big advantage, as they are well defined and clear.

Karstification (karst) period defines a long-lasting times of continental weathering and groundwater circulation which were terminated by ensuing marine transgression. Karst periods will be recognized by upper unconformities or disconformities. They may be divided into more karst phases (Bosák, Ford and Glazek 1989). During such periods interregional paleokarst (Choquette and James 1988) originated. It is related to major eustatic - tectonic events and results in karst terranes with profound erosion, a wide variety of karst features and deep, pervasive dissolution.

Karstification (karst) phases are caused by geodynamic or major climatic change, e.g. uplift or downwarping, etc. (Bosák, Ford and Glazek 1989). Local and depositional paleokarsts (Choquette and James 1988) form during such periods. Local paleokarst forms when parts of carbonate shelf is exposed, generally because of tectonism, small drops in sea level, or synsedimentary block tilting. Depending on the length of time involved, the effects of exposure can vary from minor to extensive exokarsts and endokarsts. Depositional paleokarst is that karst forms as a natural consequence of sediment accretion to sea level and to be expected within sediment packages typifying carbonate platforms. It is most commonlly associated with metre-scale cycles and smooth topographical relief.

For petroleum geologists using a broad variety of seismic records, the study of paleokarsts coincided with the evaluation of unformities. However, the importance of search for karst-hosted and karst-related mineral deposits around unconformities has been stressed already by Zuffardi (1976), Bosák (1980c), Schultz (1982) and Laznicka (1985).

Sequence stratigraphical approach to this problem is typical for Esteban (1991) who developed the application of a complex scheme of conformities and unconformities according to the character of sequence boundaries and their orders for the classification of paleokarst introducing time as important factor to distinguish them. His rather complex hierarchy of unconformities is applicable especially by petroleum geologists and seismic stratigraphy. For terranes like as the Bohemian Massif, the application of the complex hierarchic system of conformities, single and composite unconformities can be with advantage only within the paleotectonic stage of the evolution.

FOSSILIZATION AN REJUVENATION PROBLEM

Karst becomes fossil or inactive when it loses its hydrological function. The general cause for this are changes of local or regional geotectonic conditions or of global sea level. *Fossilization* can be a result of uplift or of subsidence, of marine transgression or of mass continental deposition. Continental drift (plate motion) may change the latitudinal position of karst areas in different geologic stages resulting in climatic changes, i.e. to arid or to humid, which may contribute to fossilization or rejuvenation (Bosák 1981a, 1989; Zhang 1986).

As the karst represents nothing more than open space in rocks available for deposition of sediments (both clastic and chemical)(Laznicka 1985), the paleokarst represents the trap for the stratigraphic record of variably long periods without any lithological record preserved (Glazek 1973, 1989a). The fossilization preserves features existing in certain time span conserving them. The fossilization includes stages of karst evolution, weathering, deposition, climate, etc. (Horácek and Bosák 1989). The presence of paleokarst forms imforms that the exposure occurred and nondeposition prevailed during the break. It allows to define these conditions in more detail. The character of paleokarst (karst type) enables to judge on tectonic processes and features prior to the subaerial karst development. The climatic conditions of karst iniciation and evolution can be easily reconstructed based on the typology of karst forms, on lithology of their infill and on the nature of faunistic and floristic remnants (Glazek 1973).

The absence of paleokarst forms and features on extensive areas with distinct traces of erosion and denudation is also of big importance. It informs us on the fact that karst forms developed were destructed by pronounced erosion in subaerial exposures or by abrasion of transgressions. Therefore, paleokarst of the youngest development phases is preserved (*cf.* Bosák 1980a, 1981b). Glazek (1973) believed, that the absence of paleokarst can be also the evidence of the absence of karst rocks on the surface and that such aspects can be easily conserved in correlate sediments in adjacent areas.

The fossilization of karst forms represents perhaps the most striking characteristics of paleokarst and preserves numerous sediments, fossil remnants and indirectly also the evidence of different processes during continental periods. From these perspectives, paleokarst phenomena may be considered *true conservers* of the geological and environmental past; but frequently they are "degraded" or "unreadable" because of some overlooked rejuvenation, reactivation and redeposition in their further evolution (Bosák 1987; Horácek and Bosák 1989). Sometimes containing the direct context of terrestrial and marine deposits, paleokarst can represents the *key* to the locked doors of bio- and lithostratigraphic correlation of continental and marine deposits and to the continuous geochronology of the past (Bosák 1987, 1990b; Horácek and Bosák 1989). The complex of such characteristics makes often the paleokarst the *missing link* in regional and global chronostratigraphy.

The *rejuvenation* of karst making the conserved fossil record degraded and unreadable is caused by numerous factors generally leading to the renewal of the hydrological function of the karst and of karst water circulation. It is typical for periods of introduction of energy to the whole karst/relief system. The most common cause is the increase in the hydraulic head, i.e. the lowering of the base level as a consequence of the tectonic uplift and/or the drop of the sea level. The rejuvenation is contradictory to the fossilization. The new creative and destructive karst and landform processes, deposition and redeposition, exhumation and weathering disturb the paleokarst content and cause the chaos in the primary superposition of elements in karst fillings (Bosák 1989). It resulting in the presence of deposits differing in age and genesis in the same place and in the direct relation, as documented on numerous sites of the Bohemian Massif (not only in the territory of the Czech Republic, but also in Poland, *cf.* Glazek 1989a).

The rejuvenation aspect and related processes led numerous scientists to the scepticism during the evaluation of karst sites for broader geological and geomorphological contexts. Nevertheless, numerous studies from past years showed that broadly applied multidisciplinary research of karst and paleokarst can result in reliable interpretation of "shadowed" situation of paleokarst sites. It brings results applicable in paleogeographic analyses in the broadest possible sense (*cf.* e.g. Glazek 1973; James and Choquette 1988; Bosák *et al.* 1989).

PALEOKARST RECORD

Present paleogeographic analyses have been based especially on the investigation and interpretation of marine records and/or on the analysis of huge continental basins. Such record of the geological past on platforms reflects maximum 50 to 60% of the geological time (Glazek 1973, 1989a, b; Glazek, Dabrowski and Gradzinski 1972). In reality, time covered by such records is much more shorter. Analysis of the Bohemian Massif (fig. 2, tab. 1) proved only 12 to 45% of the geological time is reflected in such records counting the time since the regression of Paleozoic sea in upper Devonian to lower Carboniferous and not from the start of the neotectonic (platform) evolution stage. From the analysis resulted that 55 to 88% of time has not been recorded in recently preserved marine or continental sequences (Bosák 1987).

The role of paleokarst as a trap of stratigraphic information was mentioned above. In the Bohemian Massif, there are some striking examples of the preservation of recently missing sediments. There are: (a) carbonate and other facies preserved in depositional and local paleokarsts, documenting the evolution of carbonate platforms and reefs, missing due to syndepositional or postdepositional erosion, and (b) sediments deposited after the evolution of carbonate host-rock sequences finished, especially deposits belonging to the Platform evolution level which disapeared in periods and phases of weathering, denudation and erosion.

The first case can be documented from the Koneprusy region, where paleokarst macroporosity and neptunian dykes genetically connected with the depositional paleokarst (freshwater - marine phreatic/vadose diagenesis) preserved carbonate facies not occurring in the record. They are missing due to winnowing of the matrix by

TABLE 1 - **The review of time data recording the evolution of the Bohemian Massif since the Paleozoic regression (from Bosák 1987)**

Region	Duration from regression (Ma)	Record totally (Ma)	Record in continental deposits (Ma)	Record (%)	Gap without record (%)
Moldanubicum	375	45	45	12	88
Bohemicum	375	48	36	13	87
Saxothuringicum	420	52	40	12	88
Brunovistulicum					
a. in outcrops	320	75	36	23	77
b. covered in Carpathian Foredeep	320	100-145	2	31-45	69-55

submarine currents and due to the abrasion and erosion within numerous hiatuses. The preservation of organodetrital limestones and limestone breccias with phosphates in depositional and local paleokarst forms of the Moravian Karst (Valkovicová 1979; Hladil 1983) can be mention, as Paleozoic examples too. Calcareous internal sediment and speleothems of late Hauterivian to Aptian age preserved in caves of local paleokarst developed in upper Jurassic-lower Cretaceous sequence of the Kotouc Hill (at Stramberk, northern Moravia, Housa 1976, 1978).

The second case is widespread in the postdepositional history, especially during the pre-upper Cretaceous and Paleogene-Miocene karstification periods. Following examples can be mention, e.g. the deposition and preservation of lover Viséan greywackes in shaft and cave of local paleokarst at Cebín (the Tisnov Karst, Bosák 1983b), the preservation of up to 50 m thick sequence of middle/upper Jurassic in broad corrosional depresion of the Moravian Karst (Panos 1962-1963; Bosák 1978a), evolution and preservation of the Rudice Formation in sunken block of the Rudice Plateau (the Moravian Karst, Burkhardt 1974; Bosák 1978b, 1980b) and near Moravsky Krumlov (Burkhardt 1962), preservation of upper Cretaceous marine and continental sediments and older weathering products in Paleogene(?) deep collapse shafts in the Koneprusy region (Bosák 1993, in print) and in pre-upper Cretaceous geological organs in the Svaty Jan pod Skalou-Bubovice-Mořina area (both in the Bohemian Karst, Röhlich and Chlupác 1951).

Results of paleokarst evolution are best preserved directly beneath the cover of marine or continental sediments, i.e. under sediments terminating karstification periods or phases. The longer is the stratigraphic gap the more problematic is the precise dating of the age of paleokarst, if not chronostratigraphically proved. Therefore, the age of paleokarst has been connected mostly with period just or shortly before the termination of the stratigraphic gap. This fact can be easily illustrated on Figure 2 for pre-Cenomanian age elswhere, for pre-Callovian in the Moravian Karst or for Westphalian/Stephanian in the central Bohemia. On the contrary, the main phase of cave origin in the Bohemian Massif (Bosák 1990b) can be dated relatively accurately thanks to paleontological finds in the Koneprusy and Javorícko Caves indicating the fossilization periods in that spaces.

PALEOKARST PERIODS AND PHASES IN THE BOHEMIAN MASSIF

The evolution of paleokarst can be connected with Variscan and Platform stages of the evolution of the Bohemian Massif. The majority of forms developed in Devonian limestones, now buried or uncovered, which were also highly metamorphosed by

Variscan Orogeny, in places. Some forms developed in Proterozoic carbonates and a limited number has been known from upper Jurassic carbonate sequence deeply submerged on eastern margins of the Massif.

The evolution of paleokarst, its origin, development, fossilization and rejuvenation have been affected by numerous lithological and structural conditions. In general, three types of paleokarsts could be distinguished (terminology *sensu* Choquette and James 1988).

Depositional paleokarst was typical by low relief, freshwater vadose and phreatic, and mixing freshwater/ marine diagenesis. Its evolution followed cyclic nature of deposition without tectonic influence and the Milankovich cycles of the 5th to 4th orders. The role of freshwater/marine mixing diagenesis was substantial. Its evolution was connected with the evolution and accretion of Devonian carbonate sequences.

Local paleokarst was the product of longer emersion caused by regressions in individual blocks. Karst relief was developed up to first hundreds of metres (shafts, dolines, caves) with well defined hydrological zonation. The evolution followed tectonic movements of individual, even very small, tectonic blocks together in the combination with cyclic events or sea level changes (unconformities of the 3rd and the 2th orders *sensu* Esteban 1991). Biozone to stage is missing. Results of the local paleokarstification can substantially differ place to place owing to the altitudinal position of emerged carbonate surface. Low altitudinal position led to undeveloped paleokarsts similar to depositional paleokarst forms even through longer hiatus, while high altitudes of distinct elevations created mature paleokarsts. Its evolution was connected with the evolution of sedimentary basins during lower/middle Devonian in the Barrandian and middle Devonian/lower Carboniferous in Brunovistulicum, where the effect of drowned platforms followed the polarity of orogenic movemets from W to E. Some of Jurassic carbonates suffered also by this kind of evolution.

Interregional paleokarst was the product of long-lasting erosion and karstification connected with deep weathering and formation of planation surfaces. There was developed substantial karst relief and deep groundwater circulation. There was a close connection to individual tectonic phases reflecting major impacts of the Alpine Orogeny leading to the rejuvenation of relief and the acceleration of karstification. There was the clear relation to marine transgressions/regressions separating individual karst phases within karst periods or to periods of mass continental deposition. This evolution was typical for post-upper Carboniferous evolution of the whole Massif. There are several typical conditions affecting the evolution of the interregional paleokarst in the Massif: (1) the prevalence of a continental regime since the Permian; (2) relatively short-lasting marine transgressions in upper Jurassic, late Cretaceous and middle Miocene times; (3) increasing tectonic activity since the late Paleogene as the impact of the Alpine Orogeny; (4) evolution of the Paratethys sea on the eastern margins of the Massif; (5) increasing relief dynamics resulting in a considerable increase of erosion rates exhuming and rejuvenating old planation surfaces and karst forms, and (6) a continual fall of the base level following stabilisation of the river system in the Pliocene (Bosák and Horácek 1981). Nevertheless, the phases of accelerated erosion were interrupted by relatively long-lasting quiet periods with stabilized conditions favouring the development of subsurface karst forms (Bosák, Cílek and Tipková 1992).

PALEOKARST EVOLUTION IN THE BOHEMIAN MASSIF: BRIEF REVIEW

The karstification periods and phases can be relatively easily distinguished within the "karst" history of the Bohemian Massif. Nevertheless, the sharp definition of individual

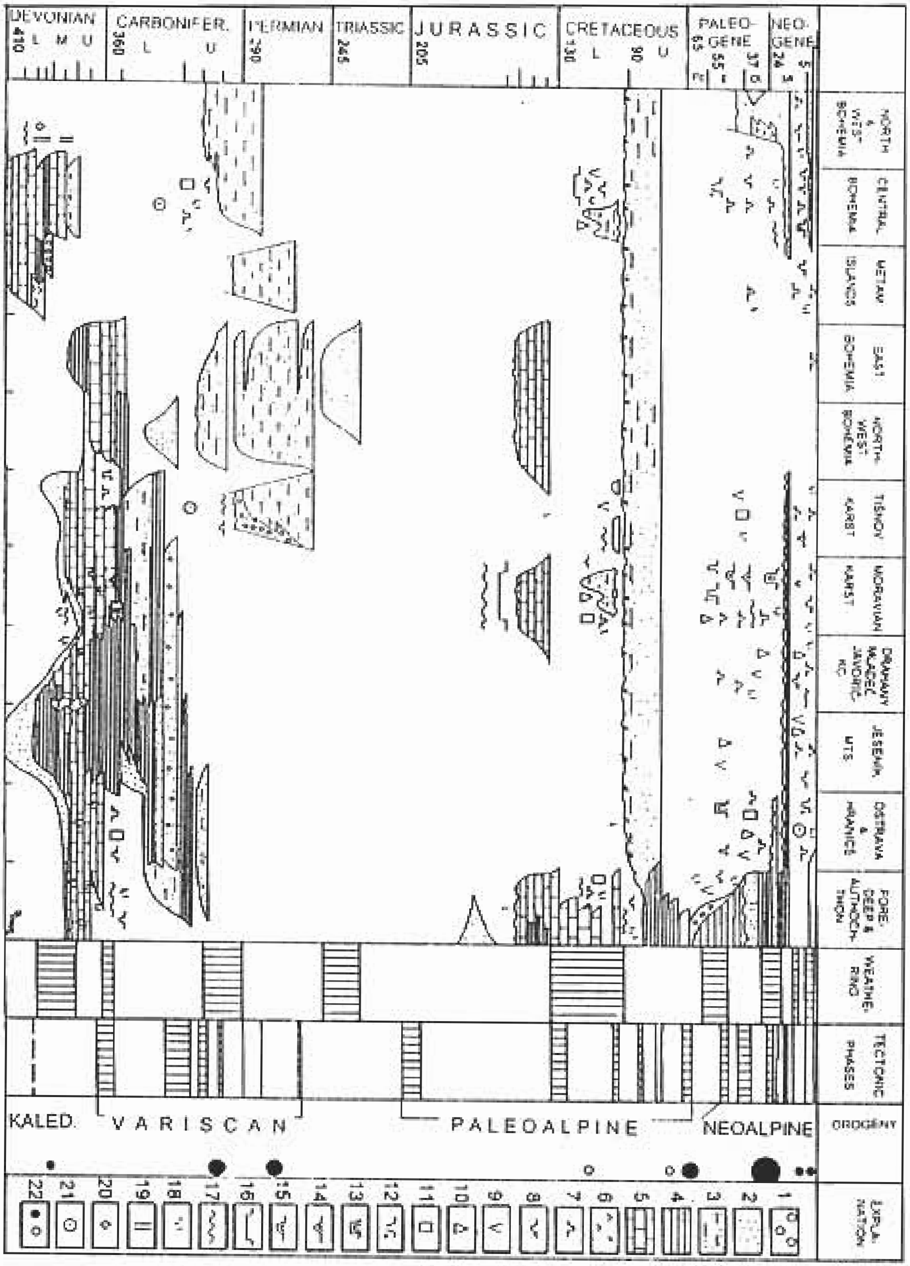

Fig. 2 -Distribution of paleokarst and sediments in selected sections of the Bohemian Massif (simplified and schematized). Lithology: 1. conglomerates, 2. sandstones, 3. lithologically variable siliciclastics (redbeds, alternation of sandstones, siltstones, sandstone, etc.), 4. shales, 5. carbonate rocks, 6. volcanics and volcanoclastic rocks, Karst forms: 7. caves, 8. dolines, 9. geological organs, 10. karst cones, 11. karst inselbergs, 12. collapse shafts, 13.-15. karst canyons and valleys: 13. canyons, 14. V-shaped valleys, 15. U-shaped valleys, 16. poljes and large karst depressions, 17. corrosional surfaces, 18. karren and minor solution forms, 19. neptunian dykes, 20. diagenetical solution macroporosity, 21. hydrothermal karst, 22. volcanic activity, black - Bohemian Massif, circle - Outer Western Carpathians adjacent to the Bohemian Massif, circle diametre approximately covers the time-span of volcanic activity.

phases is sometimes not possible. The karst evolution depended on the individual developments of the regional-geological and/or structural units/blocks. Therefore, the start and the end of some of karstification phases can mutualy overlap in different regions of the Massif as indicated by Devonian and Carboniferous paleokarstification and by the evolution of post-middle Miocene karst and landscape (*cf.* fig. 2).

There was stated above, that the basement (Cadomian) level of the Massif is characterized by the absence of the paleokarstification of that age.

Within the Variscan level there are developed rather karstification phases. They are characterized by changing paleogeographical environment with abundant transgressions/ingressions and regressions combined with high tectonic instability in certain regions and ages.

Regression of Devonian-Carboniferous seas was followed by the molasse stage. The molasse developed directly from marine deposition only in places (Lower Silesian Basin). In other sites, the continental molasse developed as thick sequences of redbeds after more or less prolonged period of nondeposition (folding, faulting, metamorphose, pluton intrusions). Karstification phases within this level was rather short-lasting with abundant depositional and local paleokarsts.

The Platform level is characterized by two prolonged karstification periods separated by the deposition of thick Cenomanian/Senonian siliciclastics on nearly all the Massif territory. Several karstification phases can be distinguished within both periods. They resulted from short-lasting marine transgressions/ingression and from the periods of tectonis instability as the reflect of the evolution in the adjacent Alpine-Carpathian domain. These processes are inprinted in the evolution of the platform cover of the Massif as follows: (1) upper Jurassic, corresponding to the platform development of the West Carpathians; (2) upper Cretaceous, corresponding with the principal Alpine folding; (3) Paleogene, characterized by intensive planation; (4) lower to middle Miocene, associated with the folding of the Outer (Flysh) Carpathians, and (5) upper Miocene to Quaternary, the stage of platform cover in the Carpathians (Malkovsky 1979). These stages of platform cover development correlate closely with individual karstification periods and phases.

The review of peridos and phases of paleokarst is given by Bosák, Horácek and Panos (1989) where the description of individual most important sites of paleokarst can be found. Paleokarstification of some karst regions were summarized also by Panos (1962, 1964, 1965); Bosák and Horácek (1981), Bosák *et al.* (1984); Bosák (1985, 1990c); Bosák, Cílek and Tipková (1992); Bosák, Cílek and Bednárová (1993), and Dvorák *et al.* (1993).

Hereafter, only short basic characteristics of individual karstification periods/phases will be given. Chart on Figure 2 summarizes the state-of-the art. Schematic and highly simplified lithostratigraphical columns for selected regional-geological units and regions of the Bohemian Massif were compiled, and completed in the review of phases of intensive weathering (kaolinic, lateritic, red earths), tectonic phases and periods of volcanic activity. Location of paleokarst sites mentioned in the text are expressed on Figure 1.

Lower Devonian (phases)

The local paleokarst developed in the Koneprusy reef (central Bohemia). The Pragian reefal and organodetrital limestones underwent the complex succession of freshwater/marine vadose and phreatic karstification (diagenesis) connected with the tectonic unrest and sea level changes. Vuggy to cavern secondary porosities developed (cm scale). The complex network of neptunian dykes originated in several phases (cf. in

Chlupáč*et al.* 1992).

Climate is supposed to be tropical, wet and hot. Correlate sediments are reprezented by the content of iron oxides derived from lateritic weathering of mainland is mentioned from overlying Dalejan to Eifelian limestones (Havlícek and Kukal 1990).

Middle Devonian (phases)

The depositional paleokarst developed in limestone cycles of the Old Red complex in the Moravian and the Tisnov Karsts, and in the Carpathian foredeep (*cf.* Dvorák 1978). The freshwater vadose and phreatic karstification (diagenesis) was responsible for the origin of smooth karstic surfaces (karren). The paleokarst was connected with the cyclic sea level changes (Milankovich' s cycles).

Climate is supposed to be hot, seasonally dry and wet. Correlate sediments are reprezented by red beds of the basal clastics themselves (the Old Red facies, *cf.* Dvorák *et al.* 1993).

Upper Devonian to lower Carboniferous (phases)

The local and in limited places also depositional paleokarst developed in upper Devonian/lowermost Carboniferous limestones in the Moravian Karst (pre-upper Tournaisian in age, Valkovicová 1979; Dvorák and Friáková 1981), the Tisnov area (pre-lower Viséan in age, Bosák 1983b), the Carpathian Foredeep and Ostrava region (pre-upper Viséan in age, e.g. Adámek, Dvorák and Kalvoda 1980; Hladil *et al.* 1993; Dvorák 1993). There developed sinkholes and depressions of different dimensions, island karst relief (Carribean type of paleokarst) and even cave horizons or level. The paleokarst evolution was connected with the tectonic uplifts in individual tectonic blocks (even relatively small) as the dominant factor, associated with global and local sea level changes (regional trangressions/regressions, local ingressions).

The general evolution and migration of paleokarsts indicate that they were caused by the polarity of the Variscan Orogeny. The termination of this evolution was clearly connected with the paradox of drowned platforms (*sensu* Schlager 1981).

Climate was supposed to be subtropical to tropical. Correlate sediments are represented by variocoloured pelitic matrix of the Krtiny nodular Limestone (upper Frasnian to Tournaisian) and of the Jedovnice breccia (Fammenian to Tournaisian) derived from lateritic weathering of the mainland, and by the lateritic material and phosphorites in the Ostrov Shales (Tournaisian) for the Moravian Karst and adjacent regions (*cf.* e.g. Dvorák *et al.* 1993).

Upper Carboniferous (phase)

The local to interregional paleokarst is supposed to develop in lower/middle Devonian limestones forming karst inselbergs within red beds of the Mseno Basin (upper Stephanian, central Bohemia). Traces of paleokarstification are represented by finds of speleothem pebbles (Bosák 1990a). Nevertheless, speleothem-like cements occur also in slope breccias, thefore this paleokarstification phase has not been verified definitely. The karstification followed the tectonic evolution of the Variscan molasse basins. The hydrothermal paleokarstification has been noted from the Bohemian and Tisnov karsts.

Climate is supposed to be dry, seasonally wet, warm (subtropical). Correlate sediments are reprezented by the upper Carboniferous kaolinization of the Plzen - Podborany group of deposits (west Bohemia, *cf.* Störr, Kuzvart and Neuzil 1978).

Permian to upper Jurassic (period)

The interregional paleokarst characterizes this period. Nevertheless, this prolonged period cannot be subdivided into individual phases owing to the lack of correlate sediments. The kartification occurred mostly on Paleozoic carbonates. This paleokarst period is characterized in the Moravian Karst by the origin of its macroform prior the Callovian transgression (Kettner 1960, Panos 1962-1963), in the Hranice Karst (north Moravia, Kodym 1960) by some supposedly Permian to Paleogene karstification, in the Bohemian Karst no identified karstification has been noted but some pre-Doggerian karstification is expected now.

For the climate no direct evidence has been available on the Bohemian Massif. Correlate sediments are represented by kaolinic clastics of the Bohdasín Formation (Bundsandstein, north Bohemia, *cf.* Prouza *et al.* 1985), and by the lateritic admixture in the Kimmeridgian breccia terminating the sequence of upper Jurassic in the Moravian Karst (Bosák 1978), no correlate sediments has been found in the Bohemian Karst.

Lower Cretaceous (phase)

The *interregional paleokarst* developed at the top of the pre-Cenomanian karst period. Paleozoic carbonates as well as metamorphic limestones (pre-Paleozoic and Paleozoic) were uncovered and karstified. This karstification phase was widespread in the Bohemian Massif (*cf.* Bosák 1981c). Its products are preserved mostly thanks to overburden of the upper Cretaceous (?Albian -Cenomanian to Santonian) platform cover. The evolution of the karstification phase followed the young Cimmerian movements rejuvenating the levelled upper-Paleozoic-middle Mesozoic surface (Bosák 1985).

The products are known in the Bohemian Karst (depressions with kaolinic sands and clays, Kodym 1923, Röhlich and Chlupác 1951; Turnovec 1980; Zelenka 1980, 1984; Kovanda and Hercogová 1986), Moravian Karst (the Rudice Formation, i.e. kaolinic sands and clays, quartzose sands, kaolins, filling extensive corrosional depressions, cone karst, Panos 1962, 1964), Vratíkov - Nemcice Karst (central oravia, mogotes, iron ores in caves, relics of the Rudice Formation, Panos 1962, 1964), Tisnov Karst (relics of sands and clays in sinkholes, Panos 1964; Bosák 1983b) and Kunstát-Olesnice (both in central Moravia, terrae calcis and lateritic weathering products in fissures of crystalline limestones, Pelísek 1975), Moravsky Krumlov (south Moravia, the Rudice Formation in sinkholes, Burkhardt 1962), Carpathian Foredeep (inselbergs on Jurassic limestones, Bezvodová and Zeman 1983), Turold Hill (Mikulov, south Moravia, tectonic clippe, planated surface with depressions and Fe-Mn incrustations on upper Jurassic limestones covered by Turonian flysh, Bosák *et al.* 1984). Some of forms are very deep. Depressions at Rudice attained more than 100 m (*cf.* Bosák 1978, 1980b) and in Prague exceeds even 120 m of the depth (Klein and Zelenka 1991) indicating deeply sunken base level both in the Moravian and the Bohemian Karsts. The Moravian Karst was drained mostly southwards into the simultaneously developing deep structures of the Nesvacilka and Vranovice Grabens (*cf.* Dvorák *et al.* 1993) dissecting eastern margins of the Massif. An ancient valley system developed in the foreland of both grabens. The characteristics of the base level for the Bohemian Karst has been unsolved yet.

The *depositional and local paleokarst* was described from the Kotouc Hill (Stramberk, north Moravia, Housa 1976, 1978). Two karstification phases in upper Valanginian and upper Hauterivian to Aptian were connected with oscillating sea level (3 to 4 order cycles)

Climate is supposed to be subtropical to tropical, wet and hot, at the end temperate only. Correlate sediments are reprezented by widespread weathering profiles under upper Cretaceous platform cover, e.g. laterites, kaolins, paleosols, kaolinization of some deposits in west Bohemia (*cf.* Störr, Kuzvart and Neuzil 1978), the Rudice Formation (*cf.* Bosák *et al.* 1979) and the Amberg Ore Formation (NE Bavaria, FRG, Gudden 1984), etc. Some bauxites are reported from adjacent Tethyan realm (*cf.* e.g. Bárdossy 1982).

Paleogene to lower Miocene (period)

The interregional paleokarst developed on all varieties of karst rocks. The products of this karst period are widespread, but without possibilities of precise dating of phases due to the general absence of paleontologically dated sites. The karst evolution was connected with the rapid continuous destruction of the upper Cretaceous siliciclastic cover uncovering karst rocks. The period terminated with the lower Badenian transgression over the eastern margins of the Massif. The period was defined as the *main phase of cave formation* in the Bohemian Massif (Bosák 1990b) with the origin and the evolution of the largest karst systems in the Bohemian, Moravian, Javorícko and Hranice (here filled with Badenian clastics, *cf.* Panos 1965) Karsts and smaller karst regions of crystalline complexes, e.g. at Blizná, (south Bohemia, Bosák 1991). Karst surfaces with depressions and conical hills developed at Tisnov (? pre-Badenian) and Lazánky (pre-Karpatian, both central Moravia, Bosák 1983), Hranice (pre-Karpatian and pre-Badenian, north Moravia, Tyrácek 1962), Branná, Vápenná, Supíkovice (north Moravia, Panos 1964), karst of the Drahany Upland at Mladec, Cervenka, Javorícko, Hvozdecko (Panos 1962, 1964, 1965), numerous sites in the Carpathian Foredeep (e.g. Zeman 1980; Bezvodová and Zeman 1983). The causes of the accelerating karstification were in the effect of the Laramide phase of the Alpine Orogeny in the combination with the climate. Planated surface originated during the Paleogene and the Oligocene (Demek *et al.* 1965, Suk *et al.* 1984). Tectonic block movements broke and dislocated the surface during upper Eocene/Oligocene (Styrian phase) and upper Oligocene/lower Miocene tectonic (young Pyrenees and Savian *sensu* Roth 1980) phases reflecting neoalpine tectonics of the Alpides. Volcanic activity in west Bohemia is connected with this tectonic activity (35-17 Ma, *cf.* Kopecky 1978).

Climate was supposed to be tropical, extremely wet and hot during Paleocene and Eocene with oscillations from tropical to Mediterranean type during Oligocene-lower Miocene. Correlate sediments are widespread and they are reprezented e.g. by kaolins at Vidnava (north Moravian) and Znojmo (south Moravia, pre-Eggenburgian), Lazánky (central Moravia, pre-Karpatian), by kaolinic and lateritic weathering products at Hranice (pre-Karpatian), by kaolinic clays at Vízina (central Bohemia), by quartzose to quartzitic conglomerates and sandstones of the Staré Sedlo Formation (northwest Bohemia, upper Eocene - Oligocene) and by pre-Oligocene kaolinitization in North Bohemian Coal Basins (*cf.* e.g. Störr, Kuzvart, Neuzl 1978; Suk *et al.* 1994).

Middle Miocene to Pleistocene (phases)

The interregional paleokarst is characterized by numerous karst sites originated probably in more individual karst phases which cannot be distinguished in detail now owing to abundant biostratigraphically dated sites scattered all over the Massif and the individual geological/relief evolution of single geological/tectonic units. Hydrothermal karstification influenced pre-Badenian caves in the Hranice Karst (Zbrasov Aragonite Caves, Kunsky 1957; Panos 1965).

Examples of young karstifications are numerous with karst landforms differing in size occurring even in the smalest outcrops of karst rocks (sedimentary as well as metamorphic ones). Kryokarst features are also common. A lot of karst landforms of the present relief are the result of this evolutionary stage however somewhat modified by Quaternary landscape forming agents (cryogenic processes, deep backward erosion, etc.).

This phase was characterized mostly by complex sequence of creation, rejuvenation, fossilization and/or destruction of karst forms. These effects were closely associated with the tectonic mobility of individual tectonic blocks and with vigorously changing climatic conditions. Neotectonic movements brought relief rejuvenation and decrease of regional base. Younger phases of the neovolcanic activity are connetec with tectonic movements. This evolution was followed by the accumulation and erosion phases with the origin of secondary higher levels in river caves. It appears that the late Pliocene/early Quaternary processes were very significant in the paleokarst fossilization that was occurred in the Massif (Bosák and Horácek 1981; Bosák, Horácek and Panos 1989).

Climate is supposed to be subtropical to moderate with cold oscillations at the end. Correlate sediment are reprezented e.g. by widely distributed paleosols of the terrae calcis group (Miocene to lower Pleistocene), or by paleontologically dated sites of upper Sarmatian age (Bohemian Karst, subtropic faunal assemblages), and of rare Pliocene and relatively abundant Biharian age (lower Pleistocene, dry and relatively warm climate of the Mediterranean type, Horácek 1980).

PALEOKARST, PLANATION SURFACES AND DEEP CHEMICAL WEATHERING

As demonstrated above, the evolution of paleokarsts are often linked with the formation of planation surfaces, as the result of the uniform process of relief-forming agents. Planation surfaces are proved to be very often connected with periods of deep chemical weathering. The prolonged is the stabilized situation with weathering the more pronounced is the progress in the planation surfaces evolution. Nevertheless, the uncovering of weathering profiles needs further tectonic instability, which, on the contrary, pronounces certain karstification processes. The clear link of tectonics, weathering and karstification can be stated.

The review of new literature on planation surfaces in the Bohemian Massif is relatively scarce. Král (1985) mentioned (1) distinct pre-Cretaceous surface connected with kaolinic weathering profiles under upper Cretaceous platform cover; (2) Paleogene etchplain with local pre-Oligocene kaolinic weathering profiles, and (3) several Neogene surfaces dissecting the Mesozoic-Paleogene global surface by neotectonic movements. Störr, Kuzvart and Neuzil (1978) mentioned surfaces connected with deep chemical weathering and dated them to (1) upper Paleogene - middle Eocene (F_2); (2) upper Oligocene - lower Miocene (F_3); (3) middle Miocene (F_4), and (4) uppermost Miocene - middle to upper Pliocene (F_5).

The review of literature on weathering crusts is also not too rich. Störr, Kuzvart and Neuzil (1978) summarized periods of the kaolinic weathering in the Bohemian Massif in general for (1) Ordovician, (2) Carboniferous - lower Permian, (3) upper Triassic - lower Jurassic and (4) Cretaceous - Miocene (?Pliocene) times. Kuzvart *et al.* (1983) listed kaolins of the Bohemian Massif originated during (1) the Carboniferous (Plzen and Podborany group of depositsin Bohemia); (2) in pre-upper Cretaceous time (Karlovy Vary and Kadan group of deposits in Bohemia), and (3) in Paleogene - lower Miocene (Vidnava, Lazánky, Znojmo, all in Moravia). Zeman (1980), and Bezvodová and Zeman (1983), based on data from deep drilling, summarized periods of intensive weathering for southeastern margins of the Bohemian Massif, the Carpathian Foredeep and the Vienna Basin as follows: (1) pre-Devonian (kaolinization, red earths), (2) middle

Devonian (karstification), (3) Mesozoic - Paleogene, (4) pre-Miocene (kaolinization), (5) middle to upper Miocene (kaolinization), (6) upper Miocene - lower Pliocene (local kaolinization, red earths, only in Zeman 1980)

The pre-Cenomanian weathering crusts underlying Cenomanian-Senonian platform cover of the Bohemian Massif are preserved on extensive areas and on wide variety of the substrate. The *laterites* developed on crystalline and ultramafic rocks, (e.g. at Letovice, Ransko, Rychnov). The *nickel-laterites* cover ultramafic rocks (at Kremze in South Bohemia). The *kaolinic weathering profiles* were found on different parent rocks e.g. of sedimentary and weakly metamorphosed origin (e.g. in the Carboniferous Mseno Basin near Melník and Benátky n. Jizerou in Central Bohemia).

To correlate periods of karstification and of formation of weathering crusts in the Bohemian Massif is relatively complex owing to the lack of well defined chronostratigraphic horizons within long periods of nondeposition and continental regime. The foreland and flanks of the Massif are covered by complex sucession of marine formations, sometimes of high thicknesses (e.g. Alpine and Carpathian Foredeeps, pre-Sudetes block). In the centre of the Massif, marine formations younger than lower Carboniferous (except of Cenomanian to Turonian) are rare and preserved in very small areas (topmost Doggerian to Kimmeridgian, Badenian). Also the extent of continental deposits of post-Variscan age is limited to certain regional geological units. Such formations don't cover the whole time span of hiatuses between marine transgression - regression cycles, but offer paleogeographic and paleoclimatic data enabling to roughly date periods of karstification (Bosák 1992).

The best link between periods of intensive chemical weathering and karstification can be stated for two periods (fig.2):

(1) During topmost Jurassic and lower Cretaceous (or pre-Cenomanian), large karst forms of tropical paleokarst are preserved under thick kaolinitic(-lateritic) weathering crusts in the Moravian Karst and some adjacent areas including Carpathian-Alpine Foredeeps. The similar situation can be stated in the Bohemian Karst (weathering crusts are thinner in general; Bosák 1985; Bosák, Cílek and Tipková 1992; Bosák, Cílek and Bednárová 1993). These phenomena can be correlated e.g. with identical forms and sediments of the northeastern Bavaria (Amberg Ore Unit, NE Bavaria, FRG Gudden 1984).

(2) The Paleogene to lower Miocene karstification (i.e. the main phase of cave formation) can be correlate with Paleogene-Miocene weathering period. The origin of caves was iniciated under the cover of upper Cretaceous rocks. Surface paleokarst of identical or somewhat younger age (Miocene) is also relatively abundant, sometimes containing kaolinic fill (Lazánky near Tisnov, central Moravia), variegated and other weathering products (Bohemian, Hranice and other karsts). Correlate sediments in nearby areas can be mentioned e.g. from Poland, where moulding sands fill karst forms in the Cracow-Wielun Upland, the Holy Cross Mountains, in Upper Silesia and the North Sudetic Depression (Bosák *et al.* 1979). The hugest accummulations in the Cracow-Wielun Upland are supposedly of the Eocene age (Gradzinski 1977).

The indications of simultaneous weathering and karstification exist for upper Carboniferous (Stephanian). Pebbles of limestones and speleothems were found in molasse red beds in the central Bohemia (Bosák 1990a). The karstification occured in the same time-span in which some of large kaoline deposits in the west Bohemia were formed (e.g. Kaznejov, e.g. Kuzvart *et al.* 1983).

The link between periods of intensive chemical weathering, origin of planation surfaces and karstification is evident in the Bohemian Massif (fig. 2). Both the intensive chemical weathering (lateritization, kaolinization) and the evolution of planation surfaces, and the karstification are linked rather with prolonged periods of relative tectonic stability. The link between intesive weathering and karstification is important indicator for prospection of economic mineral deposits in paleokarst terrains.

The link of weathering periods and individual orogenic phases is also evident from Figure Y. It can be generally stated, that weathering periods started after one phase and terminated with the following one (*cf.* middle Devonian, upper Carboniferous, Permian to Triassic, lower Cretaceous, Eocene).

PALEOKARST AND TECTONICS

Paleokarst evolution in the Bohemian Massif was closely linked with the tectonic evolution of that terrane. Tectonic evolution, i.e. individual tectonic phases of the Variscan and Alpine Orogeny determined the start and the termination of deposition in distinct regions during the Variscan and Platform levels (*cf.* Suk *et al.* 1984). Especially, the imprint of Neoalpine period in adjacent Alpine-Carpathian domain on the development of the Massif is remarkable (Malkovsky 1979). Dvorák (1993) stated that the distribution of areas with deposition and nondeposition and the character of the sedimentation in the Moravian Paleozoic was strongly affected by the movement of individual tectonic blocks as the reflection of early Variscan orogenic phases.

As stated above, the karstification was rather connected with prolonged periods of relatively stable tectonic regime and weathering. Nevertheless, the stable conditions with decreasing entropy of the system are leading to the fossilization of karst. The necessary energy to the system can be brought by the increase in hydraulic head. The entropy in the system will increase and karstification can act.

Figure Y collecting data on deposition, weathering, tectonic phases and karstification show the link between tectonic phases and the geological evolution of the Massif. Connection of Devonian/lower Carboniferous orogenic phases and the develompent of local paleokarsts is clearly visible. The continuous succession of orogenic processes is evidenced by the differing age of longer Fammenian/Tournaisian to Viséan gaps from the west to the east. In the Tisnov area, local paleokarst is covered by lower Viséan siliciclastics (Bosák 1983b), while in the Ostrava region the age of the cover is only of late Viséan age (e.g. Dvorák 1993). Similarly the evolution of lower Cretaceous paleokarst can be linked with young Cimmerian and Austrian Paleoalpine phases, when vertical movements of great blocks of the epi-Paleozoic platform occur (Roth 1980). The main phase of cave origin in the Massif (Bosák 1990b) was connected with morphogeny after the Laramide and the early Pyrenean phases of the Alpine Orogeny. The complex situation in Neoalpine period with numerous short-lasting phases and the lack of correlate sediments does not allow to clearly correlate individual orogenic phases and subaerial processes. Nevertheless, the Savian (upper Oligocene to lower Miocene) and Styrian (Ottnangian to Sarmatian) phases contributed substantially to the karst formation, fossilization and rejuvenation, as well as to the evolution of Bohemian Tertiary basins (*cf.* Malkovsky 1979) and Tertiary volcanism (*cf.* Kopecky 1978). Distinct acceleration of the deep erosion and karstification was stated after the youngest tectonic phase in the Bohemian Karst dated to early Quaternary (Biharian, Horácek 1980).

SELECTED CASE STUDIES

Four typical case studies originally compiled by the author were selected and will be mention hereafter. They reprezent different kinds of paleokarst evolution in the

Bohemian Massif. The case studies range from the analysis of relatively extensive areas of sedimentary limestones (the Koneprusy region), through the description of typical scattered (isolated) karst in partly metamorphic carbonates (the Tisnov area) up to paleokarsts in small carbonate lenses in crystalline terrains differing in the age of paleokarst evolution (the Blizná region and the Králicky Sneznîk Mt.).

POLYCYCLIC PALEOKARST OF THE TISNOV REGION (CENTRAL MORAVIA)

The karst of the Tisnov area is the typical representant of the isolated karst in highly folded and faulted terrane. Devonian carbonate rocks outcrop in two geological units, i.e. in the Moravian and the Brno units. The Moravian unit reprezents highly deformed zone of the Moravian Variscides with the nappe structure and relatively scarce and areally small outcrops of limestones and dolostones in individual tectonic slices. Carbonates of lower to upper Givetian age are lying on basal clastics of the Zlíchovian to middle Givetian age. Lower to middle Givetian is characterized by alternation of numerous clastic/carbonate cycles of variable thickness. Rocks are slightly metamorphosed (dynamometamorphose). The Brno unit is deformed in horst - graben style along the deep Permian Boskovice Furrow. Carbonate rocks outcrop on larger areas on the surface with more complete stratigraphic section (lower Eifelian to top Fammenian). The maximum thickness of carbonates attains 200 m (*cf.* Bosák 1983b).

The geological development highly influences the karst evolution. It was characterized by long periods of subaeric exposures and by relatively short interruptions by continental and/or marine deposition. Polycyclic development of karst is the results. This classical region of paleokarst was firstly fully described by Panos (1962, 1964). This case study is based on analyses of Bosák (1980a, 1983a, b). Several phases of karstification can be distinguished here.

Middle Devonian paleokarst developed during the deposition of the Závist facies unit characterized by the alternation of clastic/carbonate cycles during lower/middle Givetian (the Backovec Hill near Chudcice village). Cycles thick from decimetres up to several meters are composed of arcosic sandstones, sometimes with pebbles, rare siltstones as clastic member and of limestone/dolostone dark coloured laminites, intraclastic limestones and light grey limestones as the upper part of cycles. The depositional paleokarst developed in some of cycles in the carbonate member. Karst features are smooth with very small vertical amplitude. Uneven corrosional surfaces prevail, mostly developed in dark laminites or under intraclastic limestones. In places, small karren developed on top of carbonate layers.

Lower Carboniferous paleokarst is developed in the Frasnian-Fammenian limestones of the Cebín Quarry. The karst shaft developed on overthrust continues for several tens of metres by the horizontal level. The shaft is more than 5 m deep and 2-3 m wide. The cave level had variable width from about 0.5 to 2 m. The fill was composed of lower Carboniferous greywakes (the Culm facies) presumably of the lower Viséan age. The upper part of the shaft was further filled with Permian continental redbeds (sandstones, siltstones, shales) and by Neogene (lower Badenian) ochreous and grey calcareous clays. The fill was terminated by two horizons of Quaternary sandy/pebbly deposits. The local paleokarst developed during topmost Fammenian to Tournaisian emersion of reefal limestones and before deep submergence beneath flysh deposits (effect of drowned platforms). During Variscan folding, the karst system was disturbed by overthrusting.

Lower to upper Carboniferous, maximum up to the Autunian (basal Permian) were characterized by the Variscan folding and the evolution of hydrothermal paleokarst in the Kvetnice Hill and at Heroltice village. Some small karst cavities were formed by hydrothermal solutions. They were filled with siderite, ankerite, barite, calcite, aragonite and rare Pb and Cu sulfides. Some of caverns contain sphalerite-galenite-quartz assemblage (Cesková 1978). One cave was once accessible with fillings by unconsolidated fine limonite and wad, and with relic barite on walls (Slezák 1954).

Upper Carboniferous to lower Permian karstification at Cebín village preceeded the mass continental deposition in the Boskovice Furrow. Karst forms are represented by uneven corroded surface with widened fissures and initial karren evolution. The karstified surface was covered by reddish brown continental redbeds (late Stephanian-Autunian). The karst relief was developed in dry and hot climate unfavourable for more pronounced evolution of forms.

Lower Cretaceous paleokarst forms are the constituent of widely distributed interregional paleokarst of this age in Moravia (Bosák 1981). In the Tisnov karst, only relics were found. They are reprezented by small depressions and corroded fissures filled with the Rudice Formation in the Cebín Quarry (Bosák *et al.* 1979). Exhumed karst plateau with cockpit-like elevations and depressions described Panos (1962) from the Obora Hill. All features developed in favourable climatic conditions prior the Cenomanian marine transgression.

Paleogene interregional paleokarst is scarcely preserved at Cebín village. Not extensive geological organs and corroded fissures filled with variegated weathering products are attributed to this phase. Karst forms developed after the erosion of upper Cretaceous sedimentary cover. They are covered by the Badenian sediments.

Neogene karstification was connected with the episode of the lower Badenian ingression and the intensive faulting of the region. Karst evolution was strongly influenced by variations of the altitudinal position of the base level. The *pre-lower Badenian* evolution of karst is documented by numerous complex depressions (sinkholes, geological organs, several hundreds of metres wide and up to 60 m deep) filled with the succession of freshwater sediments (clays, kaolinitic clays and kaolins separated by lignite seams and fossil soils) at Lazánky and Marsov villages. The fill was dated to Helvetian/Tortonian, i.e. Karpathian by fish remains and Characeans (Smetana 1924). Also some smaller caves developed at that time being filled with kaolinitic sediments (Skácel 1954). In evirons of Malhostovice village, pre-Badenian karst pediplain with karst towers or inselbergs developed (Panos 1962, 1964, Bosák 1980). Positive forms are more than 50 m high.

Lower Badenian paleokarst was connected with the Badenian (Moravian) marine ingression and the evolution of the Tisnov fault zone. The sea invaded into very old valley system founded even during lower Cretaceous age and entrenched by the Paleogene paleoriver network directed into rapidly sunken Nesvacilka Graben in the eastern margins of the Bohemian Massif. During Paleogene, the graben attained depths up to 1 000 m (Zeman 1980) and originated great hydraulic head and potential for karstification. The graben structure was filled gradually from Oligocene to Badenian. The Tisnov fault zone constituted narrow graben filled with lower Badenian clastics, predominantly composed of calcareous clays. The lower Badenian sea flooded pre-Badenian karst relief with karst towers. When emerged, local paleokarst developed on them. There are small spherical caves originated in nearshore environment at interface of fresh and sea water (similarly to processes described by Rudnicki 1980). Other small caves can be attributed to the surf action (abrasion caves, fig. 3). The syngenetic cave formed in the Badenian abrasion breccias on the top of one of karst towers (fig. 3).

Post-Badenian karstification was connected with the exhumation and evolution of

Fig. 3 - Exhumed Badenian paleokarst at Malhostovice near Tisnov. Upper photo - spherical cave at the slope of the karst tower, lower photo - karst tower with syngenetic cave in the top (photo by P. Bosák)

pre-Badenian relief and the neotectonic activity. The Badenian fill attained the thickness of several hundreds of metres, more or less completely covering the pre-Badenian relief. The tectonic unrest caused relatively rapid exhumation of the fill. The origin and evolution of nearly all caves in the region was connected with those processes. The largest cave of the region, Král's Cave at the Kvetnice Hill, originated when Badenian sediments filling the Tisnov fault zone were partially exhumed and limestone appeared as the outcrop. The upper entrance of the cave attain all features of the horizontal ponor. Further, the cave developed during the continuous fall of the base level as the Badenian fill was exhumed. The prevailing vertical morphology of that and other caves indicates that the exhumation was slow and relatively regular except of short-lasting stable stands connected with the formation of larger vadose spaces or "levels".

Pliocene and Quaternary processes were integral part of the post-Badenian evolution characterized by neotectonics, backward erosion and exhumation of older sediments. Small cavities, karren and corroded fissures filled with red soils, limonitic crusts amd Fe-Mn concretions originated presumably in *Pliocene-early Quaternary*. The fossilization phase of subhorizontal cave systems at Lazánky village was connected with early Quaternary Biharian stage and with the post-Biharian (?Holstein) interglacial (I. Horácek *pers.comm.*) similarly to other regions of the Bohemian Massif (e.g. karsts at Javoricko, Mladec and Sovinec, *cf.* Bosák, Horácek and Panos 1989).

The Tisnov Karst thus represents the classical area of the Bohemian Massif with the origin and evolution of the polycyclic karst in the complex geological structure and scattered small carbonate outcrops. The karst and morpholohy evolution were strongly affected by relief-forming process closely related to the Variscan Orogeny and to the direct effect of the Alpine Orogeny in the nearby foreland of the Bohemian Massif.

PALEOKARST OF THE KONEPRUSY REGION (BOHEMIAN KARST): THE EVOLUTION OF KARST AND CAVES

The Koneprusy region is typical by specific facies development of the lower Devonian of the Barrandian Basin. The reefal and organodetrital Koneprusy Limestones (Pragian) is overlain by the Suchomasty Limestones (uppermost Zlíchovian to Dalejan), Acanthopygae Limestones (Eifelian) and siliciclastics of the Srbsko Formation (Givetian, Chlupác *et al.* 1992). Limestones show good lithification in the stage of very deep burial. They are folded, often with overthrusts and densely faulted and fissured. The Koneprusy Devonian represents complicated syncline structure separated to two individual synclines separated by flat anticline.

Up to now, the origin and development of karst forms in the whole Barrandian region has been connected with the evolution of the terrace system of main rivers, i.e. Berounka and Litava Rivers and their paleoequivalents. The origin of caves has been linked especially with the Quaternary geomorphological cycle. The evaluation of exploration in the Koneprusy region (1952 to 1993) and of the speleological investigation of active and old quarries brought some new knowledge and interpretation possibilities (Bosák 1993) for the whole Barrandian Basin, whose limestones landscapes are known as the Bohemian Karst. The case study is based on studies of Bosák (1993, in print) and on new unpublished synthesis.

Karst forms in the landscape. The presence of caves in the northern part of the region, in the Zlaty Kun Hill, is concentrated to the belt situated somewhat to the S-SW from the line of the Ockov ovethrust, limiting limestone outcrops. There are situated not only the Konepruské Caves developed in 3 levels, but also about 19 smaller caves in levels corresponding to the middle and lower levels of the Konepruské Caves. Caves in other smooth hills (Na Voskope, Plesivec) are relatively small. The common feaures of all smaller caves can be summarized as follows: (1) they are more or less isolated without distinct known interconnection, and (2) they have character of upward blind and inclined phreatic channels or irregular phreatic corrosional spaces. The part of caves is completely colmated by sediments as old as upper Sarmatian to lower Pliocene (Horácek 1980a, b).

Karst features in boreholes can be characterized into several categories: (1) *karst cavities*, i.e. space mostly filled with sediments - reworked upper Cretaceous and Tertiary deposits and in situ Tertiary and Quaternary deposits, sometimes with speleothems. Only small percentage of cavities is completely or partially empty; (2) *intergranular karstified* carbonates represent in situ decomposed wackestone and grainstone into calcareous sandy eluvium during very intensive process deeply below the base level; (3) *karstified zones*, without detailed specification are reprezented by widened fissures, bedding planes or cracks, often representing the epikarst zone; (4) *infiltration kaolinization* when the carbonate rocks is altered to clayey-silty material by in situ cold metasomatosis with the transport of clayey-silty particle during calcite dissolution as a result of aggresive water percolation under wet-hot climate on the surface, and (5) *epigenetic reddening* caused by weathering processes and Fe transport. The process was tectonically controlled and influenced by lithology/porosity and its products occur in distinctive levels as the marker of fossil piezometric levels. The terms intergranular karstification, infiltration kaolinization and egigenetic reddening were introduced by Bosák, Cílek and Tipková (1992) and explained by Cílek, Bosák and Bedná_ová (1995).

Devonian karstification. Local paleokarsts originated during Lower to lower Middle Devonian. Freshwater vadose and phreatic karstification was connected with reef emersions and the origin of freshwater lens. Several phases can be dated to the interval of Pragian (lower Devonian) to Givetian (middle Devonian). Originated macroporosity (vuggy and cavern types) was filled with clayey dolostone to dolomitic claystone, dark coloured (Bosák 1993). Connected features of neptunic dikes filled with several generation of all lithostratigraphic units can be connected with blue holes of recent Bahamas (Smart *et al*. 1988). It seems that the system of this paleoporosity influenced all further subsurface karstification processes. The origin and evolution of the Koneprusy reef, its emersions and the evolution of neptunic dykes and hiatuses in the stratigraphic sequence were influenced by the tectonic movements of the basement block as the echo of late Caledonian phases.

Carboniferous to Cenomanian karstification. During Variscan Orogeny (upper Carboniferous), hydrothermal karstification originated. Smaller caverns filled with hydrothermal dolostone and crystalline calcite occur on or at thick calcite veins. Pre-Cenomanian karstification period started in the upper Carboniferous. No known subsurface karst forms have been known. There are only some relics of surface forms and sediments. The period was finished by extensive marine transgression.

Paleogene to lower Miocene karstification was connected with gradual but rapid erosion of the upper Cretaceous platform sediments (siliciclastics prevail). Intensive subjacent karstification started when the Cretaceous cover was substantially thinned by intensive weathering (Paleocene and Eocene) and by backward erosion to permeable Cenomanian sands and gravels. Ponors in the multiple rank (*sensu* Ford and Williams 1989) appeared at the margins of limestone subcrops and outcrops (fig. 5). The development of basic network of passages led to the origin of extensive caves which presently contain various fill sometimes reworked completely. The time of cavern origin can be linked with the main phase of cave evolution defined by Bosák (1990c) for the whole Bohemian Massif and dated to middle/upper Paleogene.

The evolution of caves was connected with prolonged periods of stabilized base level (*cf*. Palmer 1987) represented by the origin of extensive aluvial plains in the Bohemian Karst (Bosák, Cílek and Tipková 1992). This evolution was indicated also by older morphological analyses (e.g. Ovcarov 1973 or Lysenko 1987).

The morphology of caverns shows, that they mostly originated in the phreatic regime. The cavern shapes have typical morphological features of batyphreatic or phreatic caves (*sensu* Ford and Ewers 1978) with multiple loops, and inclined ascending and descending passages connected by shorter or longer subhorizontal tunnels or channels. Phreatic corrosional features and widening of channels is also typical and led to the origin of irregularly shaped and sized domal caverns. The horizon equivalent of the middle level of the Konepruské caves was later morphologically reworked at oscillating piezometric level in the vadose regime. The concentration of cave close to the thrust limit of limestones at the north is most probably caused by paleohydrogeological and paleohydraulical features of underground drainage and hydraulic head towards the hydraulic barrier of the Ockov overthrust. Phreatic caves discovered in quarries and boreholes represented inflow channels connecting the ponor area with the barrier along tectonic directions of N-S and W-E directions (fig. 6 and 7). Some caves collapsed originating irregular to circular pipes filled with the upper Cretaceous and Paleogene deposits (fig. 4 and 5). The depth of pipes more than 90 m was proved by geophysical mesurements.

Fig. 4 - The view of excavated upper Cretaceous sediments from irregular depressions in the Velkolom Certovy schody Quarry at Koneprusy (photo by P. Bosák, September 1994)

Fig. 5 - The morphology of excavated collapse pipe in the Velkolom Certovy schody Quarry at Koneprusy (photo by P. Bosák, September 1994)

Miocene karstification. The gradual diminution in the karstification can be observed. It was caused by tectonic/morphological features leading to the shift in the position of the piezometric level. Gradual decrease of the base level resulted in (1) the fossilization of some of inflow channels, and (2) the evolution of vertical connections and vadose invasion caves. The main periods of fossilization can be dated since upper middle Miocene (Sarmatian and younger colmatage of Oligo-Miocene caves). Younger caves were connected with mixing corrosion under about two to three further phases of the stabilization of broad alluvial plains. Large lakes developed in caves. Some older ones were dissected and somewhat displaced by neotectonic movements (Ovcarov *et al.* 1972).

Pliocene to early Pleistocene karstification. The continuing fossilization with middle Pliocene and Biharian phases was typical feature of this evolutionary phase. The last neotectonic movements are dated back to Biharian (cca 1.1 Ma) in the Konepruské Caves (Horácek 1980).

Quaternary processes. Pleistocene to Holocene was characterized by intensive backward erosion owing to rapid entrenchment of main river of the region (Berounka) some 90 m down at the end of Biharian and by continuous evolution of superficial karstification (epikarst zone). Some minor caves were maybe inserted during shorter stabilization of base levels.

Paleohydrogeological model. The presented paleohydrogeological model of the evolution of caves in the Koneprusy region abandons up to now prefered theory on continuous evolution of cave levels in the connected with the origin of terrace river system (e.g. Hromas 1968). It is based on following postulates:

(1) The predisposed network of lower - middle Devonian diagenetic porosity was several times utilized by younger karstification phases influencing the space arrangement of subsurface karstification processes. Strong tectonic controll can be stated.

(2) The evolution of some karstic porosity to macroporosity during pre-Cenomanian (mostly upper Jurassic - lower Cretaceous) evolution of landscape cannot be completely excluded. It was connected with the stabilization of broad alluvial plains characterized by mixing corrosion of river and ground waters in limestones.

(3) The destruction of the upper Cretaceous platform sediments underwent in wet and hot climates during Paleocene to Oligocene. This was connected with the evolution of: (a) ponors at margins of limestone core of synclines; (b) infiltration routes under a cover of permeable Cenomanian sediments (mostly sandstones), and (c) ponor network in multiple ranks and multiple lines at the margins of Silurian and Devonian subcrops and outcrops (fig. 6).

(4) The evolution of cave systems was in deep phreatic zone with cave horizons with multiple loops and local horizontal features. The cavern origin (and the karst groundwater circulation) followed main tectonic scheme, i.e. NNE-SSW to NNW-SSE tension open fractures and faults and WNW-ESE to WSW-ENE compressional faults to overthrusts. The main characteristics of caverns can be summarized as follows: (a) in areas close to ponors cave have mostly character of circular, mostly phreatic tunnels. Their diametre increases with the distance from ponor areas, and (b) in area close to the main hydraulic barrier, caves are irregular, vertical with subhorizontal "levels". They are characterize by maze to labyrinth nature and irreular morphology of shallow phreatic to vadose lake-filled rooms (fig. 7).

(5) The main hydraulic barrier has been representing by the Ockov overthrust forming the NE closure of limestone syncline. It caused the upwelling of water, the increase in piezometric level and water discharged along the thrust line in NW and SE directions. The zone, tens to first hundreds of metres wide along the overthrust is typical by the absence of caves due to the compressional nature of fissure network.

(6) The evolution of lower deep phreatic cave horizons was later dependent on the decrease of piezometric level as a consequence of climate aridization and/or change of regional base level. Base level subsided due to uplift connected with Miocene volcanic phases. Old piezometric levels are marked by iron precipitates inside the carbonate massif. Complete removal of Cretaceous platform cover led to formation of carbonate outcrops and resulted in the retreat of limestone slopes and shift of ponors in the centripetal manner.

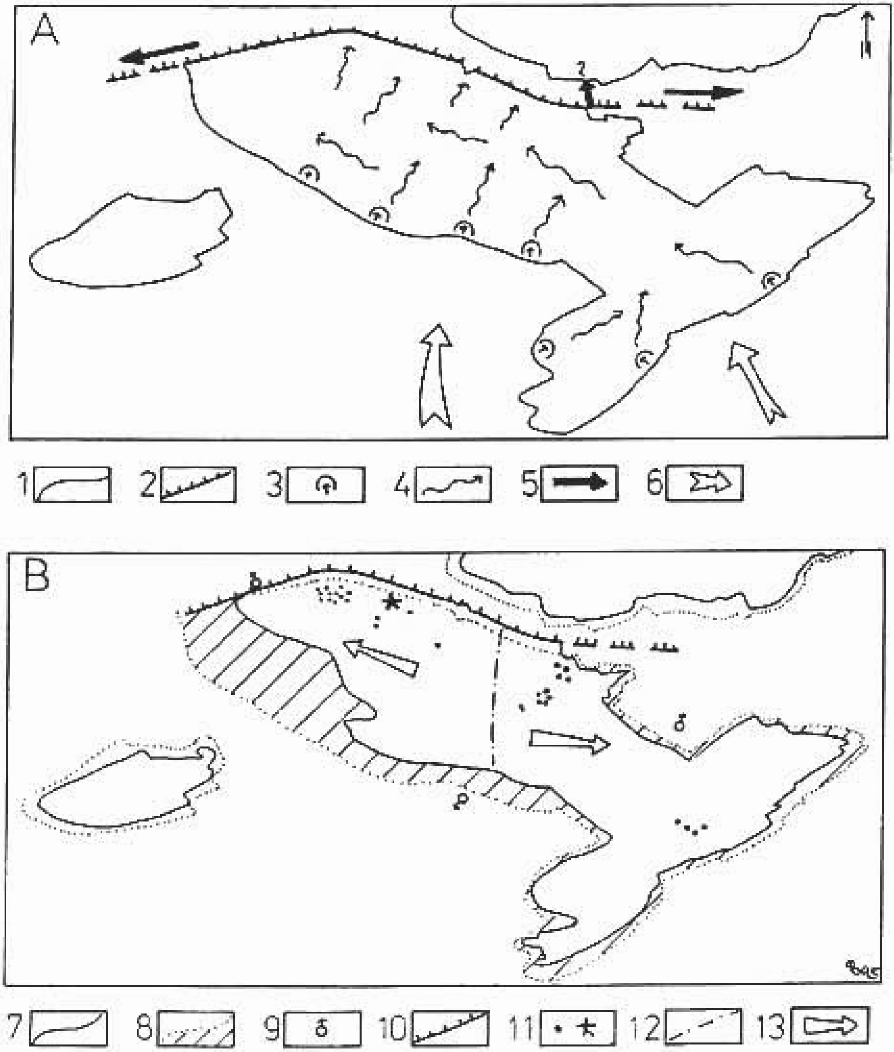

Fig. 6 - Evolution of drainage in the Koneprusy region in plan (after Bosák, in print)

A. The main phase of cave origin; 1. limits of limestone subcrops and outcrops, 2. Ockov overthrust, 3. main directions of water inflow to karst, 4. ponors (schematically), 5. flow direction of karstwater
B. Present situation; 6. present limits of limestone outcrops, 7. limestone slope retreat, 8. caves, 9. karst springs, 10. water divide, 11. flow direction of groundwater.

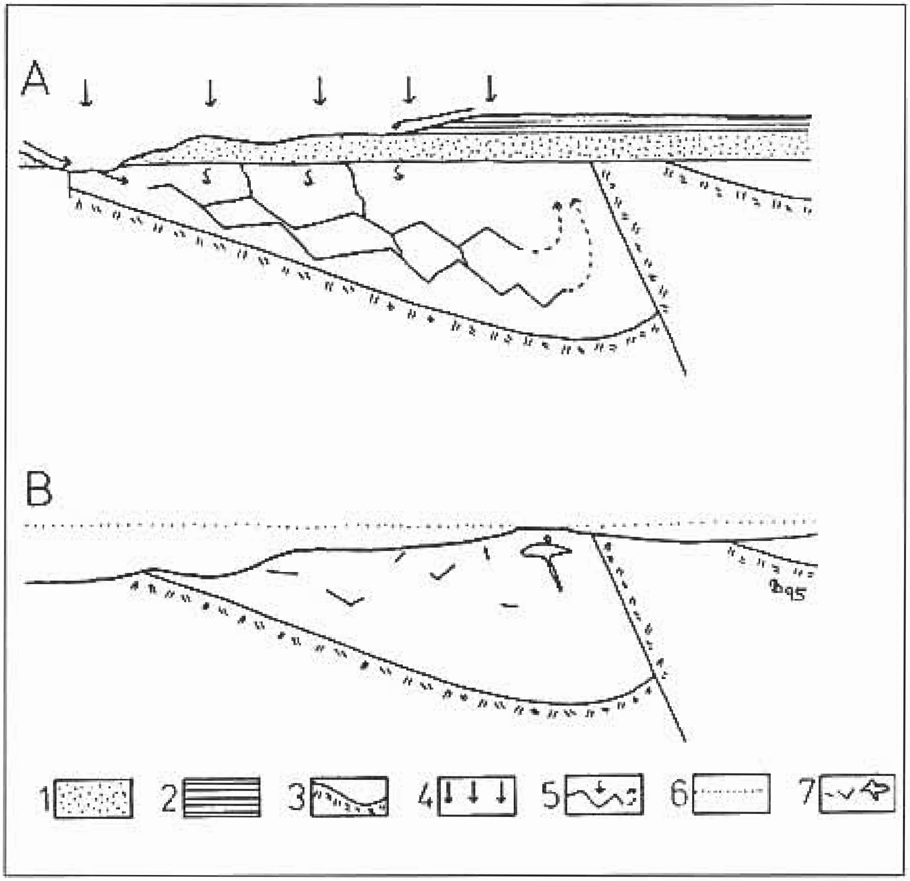

Fig. 7 - Schematic section of the syncline structure of the Koneprusy region in the time of the main phase of cave origin (after Bosák, in print)

1. Silurian and Devonian limestones, 2. Cretaceous siliciclastics, 3. Ockov overthrust, 4. ponors, 5. groundwater circulation paths, 6. caves (known at present), 7. groundwater discharge directions.

TERTIARY PHREATIC PALEOKARST SYSTEM AT BLIZNÁ, SOUTH BOHEMIA

The Blizná graphite field is situated in south Bohemia at the Lipno reservoir in the Vltava valley. Large karst caverns were opened during two catastrophic floods in the Václav Mine (January and February 1983). The karstogenetic evaluation was published by Panos and Pucálka (1989, 1990), Pucálka (1990) and Bosák (1991b). Karst hydrogeological study is presented by Bosák and Koros (1991). There, details can be found. The case study is based on study of Bosák (1991b).

Geology. Metamorphosed carbonate rocks in the Varied Group of the Moldanubicum (Proterozoic or lower Paleozoic) form locally substantial part of the rock sequences consisting of gneisses, migmatitized gneisses and locally migmatites. Carbonate rocks are developed in two horizons. They are separated by graphite-bearing deposit level.

Their thickness varies between several metres to tens of metres. The Varied Group is here highly folded and strongly faulted.

Geomorphology. All karst fetures belonging to the Moldanubian of this region and adjacent areas belong to the *scattered* karst type. The main geomorphological unit of the region is the fault limited Vltavice furrow as a part of old drainage network of the Sumava Mts. The foundation of the Vltava paleonetwork is dated from Helvetian up to lower Tortonian (i.e. upper Karpathian to lower Badenian in the stratigraphic scheme of the central Paratethys; Malkovsky 1975, 1979). The drainage was directed to the SE into the region of Alpine Molasse Basins (Kinel 1930). In the dependance to the movement of local structural blocks during the Alpine Orogeny it seems, that the furrow lost its hydrological function at the end of Miocene (Sarmatian) and in Pliocene. The drainage was stoped (Malkovsky 1979). Following the movement of the Ceské Budejovice Basin and uplift of the Sumava Mts., gradient of rivers increased and rivers entrenched their basement. Back erosion of the Vltava River during Pleistocene beheaded the old form of the Vltavice furrow.

The whole area is highly weathered. The present relief represents, most probably, partially exposed basal etchplain surface. The Vltavice furrow eroded the surface. Gneisses of different types are deeply weathered into the loose eluvium into the depths of 20 m sometimes up to 65 m. Limestones are weathered into sandy eluvium with low clay contents. According to geomorphological longitudinal section it can supposed that the main erosional form of the relief is represented by flat, broad and step-like pediment. It is transformed into forms resembling cryopediments, in places. Altitudinal dissection of the pediment was caused by young activity of some tectonic lines. Pediments are entrenched by young erosion and by the network of present drainage paths. The evolution of pediment followed, most probably, the end phase of the kaolinic-lateritic weathering and preceded the foundation of the Vltavice furrow or was simultaneous with its evolution in time and space.

Karst in overlying limestones (with the respect to the graphite-bearing horizon) represent *contact* type of karst developed by intensive karstification along lithological/tectonic boundary of nonkarst and karst rocks. Karstified zones have several metres in the width. Lithologically influenced free caverns, irregularly-shaped cavities, chimneys, anastomoses, bizare spongeworks and boxworks and small ovate or irregular channels and other forms have been surveyed. They are mostly filled with sandy eluvia or collapsed blocks.

Karst in underlying limestones are reprezented by large water-filled karst caverns uncovered by mine and detected by underground boreholes. Caverns are less or more steeply inclined tubes with diameters of 4 to 7 m. Caves with loop-and-bypass morphology have known heigth of approx. 22 m.In the upper part of caves, horizontal to subhorizontal passages are developed. Caves are of distinct phreatic morphology. In horizontal sections, there are developed features of vadose entrenchments and change of primary phreatic forms. Sediments in caves form stratified sequence of allochthonous deposits. Except of huge caverns, also contact type of karst has been detected with similar characteristics as in the overlying limestone horizon.

To solve the general picture of karstogenesis in the region studied, there are very important results of deep borehole Novosedly NV-1 situated about 15 km to NE from Blizná (Tichy 1984, pers.comm.). The borehole detected deep circulation of groundwater in the artesian regime.

Natrium-hydrogencarbonate chloride waters with temperature of 30 to 36°C circulate in the depth of 1 200 to 1 500 m. The existence of such deep circulation of groundwater also in carbonate rocks indicates the possibility of evolution of karst porosity (*s.l.*) in phreatic or deep phreatic conditions even in metamorphosed, i.e. crystalline limestones. System of karst porosity and of embryonal vugs was later exploited for the development of karst caverns in shallow phreatic and vadose conditions. Regional deep circulation of groundwater is fed by infiltrating precipitations. Water was enriched in some elements in somewhat elevated temperature (corresponding to the geothermal gradient) during decrase. The absence of free CO_2, although discussible, can indicate low participation of juvenile waters or of hydrothermal fluids (*s.s.*) in the formation of groundwater sampled.

Karstogenetic model. The character of karst forms in overlying and uderlying limestones substantially differs. In the *overlying* horizon, the karst is of the contact type developed in vadose conditions in relation to the weathering and the character of undergound drainage. Irregular cavities of the pocket type originated by this way. They are partly or completely colmated, mostly nearly vertical forms with associated channels of the epikarst type.

The morphology of caverns in *underlying* limestone horizon, as well as their organization related to lithology and structure, indicate that they are a component of well developed system of phreatic caves. Panos and Pucálka (1989, 1990) interpret them as cave system developed in the upper, dynamic zone of the shallow phreatic environment. The system represents caves of the 2nd stage from the "four stage" model of Ford and Ewers (1978), i.e. caves with numerous phreatic loops and short vadose bypasses in their upper parts. Their phreatic morphology is of a primary nature while vadose modifications are, most probably, connected with later evolution. It seems that the cave system developed in relatively dynamic upper level of the shallow phreatic condition. The inconsistency of the batyphreatic morphology arisen from shallow phreatic zone, we can explain by the geological structure. In underlying limestones, conditions of confined aquifer appeared (artesian confinement) with favourable hydraulic and hydrochemical environment for the evolution of cave of the bathyphreatic type and morphology. Cave origin, therefore, took place in relatively shallow subsurface. After piezometric level somewhat dropped, partial change of morphology in vadose conditions occured as well as the mass deposition of resedimented gneiss eluvia. Caverns, which have been known now, are not isolated caves, but they are constituents of larger cave system originated in environment of concentrated water inflow and free outflow from the system (Panos and Pucálka 1989).

Phreatic stage. The phreatic stage of the evolution is connected with the period characterized by sufficient quantity of precipitation available for infiltration and swallowing of surface waters into the karst subsurface. Distinctly humic climate was interpreted in the Bohemian Massif and adjacent areas during nearly whole Paleogene with short-lasting somewhat less humid or colder phases.

Especially humid lower Oligocene has been documented. Intensive kaolinic-lateritic weathering took place during Paleogene. Its main phase or culmination, respectively, can be dated into Eocene. Correlate sediments are reprezented by basal formation of the North Bohemian Brown Coal Basins (Staré Sedlo Formation - Eocene to Oligocene; Knobloch 1990) with numerous features documenting the evolution of the weathering, floral remains (e.g. Knobloch and Kvacek 1990), etc. The phreatic karstogenetic phase was bounded to the course and cessation of weathering with relatively stable tectonic regime (Malkovsky 1979). Karstification was characterized by conditions of intensive groundwater circulation, at least partially in the artesian confinement. The drainage followed either fault systems and/or was active by the transfer into the fissure systems and porous environment overlying the deposit (fig. 8). The role of increased aggresivity of water due to sulfide decomposition cannot be excluded. The phreatic karstogenesis in

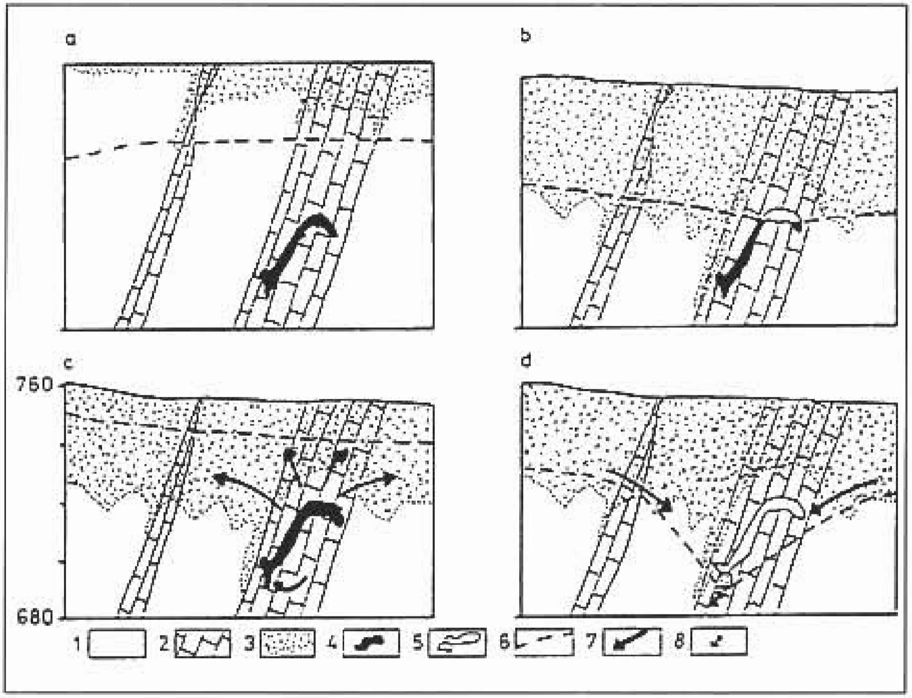

Fig. 8 - Schematic section of the evolution of karst system of the Blizná deposit (after Bosák 1991b)

a. phreatic stage, b. vadose stage, c. subrecent stage before mine dewatering, d. present state, 1. non karst rocks, 2. crystalline limestones, 3. weathered zone, 4. water-filled caves, 5. mine gallery and drained caves, 6. groundwater level, 7. groundwater flow direction, 8. karst spring in the mine.

the Blizná area can be dated into the *"main phase of cave formation"* of the Bohemian Massif defined and dated by Bosák (1990b) into Oligocene-lower Miocene.

Vadose stage. The vadose karstification phase is connected to the stabilization of the piezometric level which followed the formation of the erosion base level in the area. Its stabilization for longer time period corresponded to quiet phase of the tectonic evolution of the Bohemian Massif at the Oligocene/Miocene boundary. Supposed hydrological activity of the Vltavice furrow dated by Malkovsky (1975, 1979) into the middle Miocene (Helvetian to lower Tortonian) fits into the model. The bottom of the Vltavice furrow represents the erosion base level for broader area as proved by levelled bottom altitudes in a long distance. Vadose elements and concentration of karst features on the 2nd mine level, piezometric limit (*sensu* Palmer 1972, 1987) in opened caves, cavities in some boreholes indicate the connection with the fossil Vltava valley. However the whole system is affected by neotectonic movements. The drainage of the karst aquifer took place by the transfer of karst water into the surficial weathered zone and by masked or hidden springs to the valley network. The final dissection into the present hydrogeological blocks and drainage basins (catchment basins) resulted from tectonic movements and reorganization of the morphological plan, drainage network, etc. during late Miocene, Pliocene and early Pleistocene.

COVERED KARST OF THE MRAMOROVY QUARRY (NORTH MORAVIA): EVOLUTION MODEL

The studied region is situated in the southern slope of the Králicky Sneznfk Mt. along the upper course of the Morava River. There, surface and subsurface karst features occur in monoclinal strips of crystalline limestones of the Stronic Group (fig. 9).

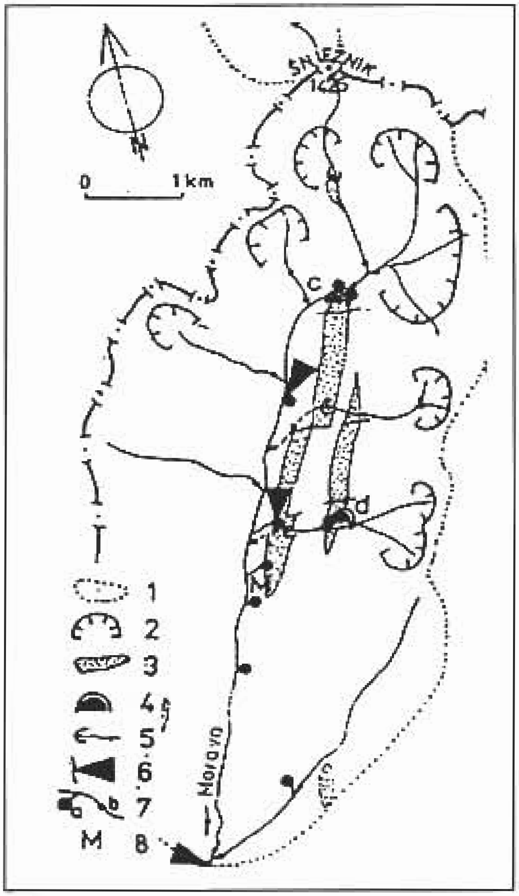

Fig. 9 - The plan of the Morava River Basin (courtesy of J. Rehák)

1. borders of river basins
2. nival basins
3. crystalline limestones
4. important caves:
   c. Tvarozné díry
   d. Pacltova jeskyne
6. ponors
7. smapling sites
8. meteorological station

(Proterozoic-?lower Paleozoic). They are surrounded by different types of gneisses. The limestone thickness attains up to 300 m. They are covered by deluvia and by variegated weathering products with limonite at the base (in karst depression). The river bed of the Morava River is deeply entrenched here with the total depth of 500 m. Outcrops of crystalline limestones are expresses in the valley morphology only rarely. The case study is based on analyses of Bosák (1982, 1994), and Bosák and Hysek (1994 a,b).

Karst forms. Surface karst forms are developed subordinarily. Two to three levels of caves (cave level in non genetic sense here) are developed. The upper one is situated several metres below the surface. Caverns of channel type are dissected by vertical karst forms filled with sediments. The middle level consists of caves partly accessible for the man. The lower level was proved by drilling in the depth of about 100 m. The forms of the covered karst are extensively developed. Limestones beneths sediments are deeply dissected by depressions into the form of conical elevations sometimes with sharp forms resembling clint-and-grike morphology. Some of them are uncovered protruding above the surface and they are partly destructed by the congelifraction. The heigth of elevations diminishes upslope.

The problem. The Mramorovy Quarry site and surroundings has intteresting geological and geomorphological position. Therefore, the genesis of conical shaped karst forms and sediments in depressions undergo the controversial discussion (Krutsky 1973, Madera 1983 and Bosák 1982). The karstification in wet and warm climate (?of the tropical type) during Tertiary was assumed (e.g. Madera 1983, Demek and Madera 1982). Bosák (1982) expected that conical forms of karst represent great karren (clint-and-grike) originated by strong corrosion by thaw waters during the Quaternary. Variegated weathering products in depressions are redeposited sediments.

Sediments. Mineralogical and petrological analysis allow to distinguish three genetically different kinds of sedimentary fillings (except of solifluction mixtites covering the relief): (1) *lithologically variable fillings* among karst cones are characterized by quartz and muscovite, in places by feldspars, vermiculite, sepiolite, chlorite, and mixed-structures vermiculite-chlorite. Kaolinite is totally absent. The heavy minerals are composed dominantly of instabile minerals with prevailing pyrite, epidote and locally apatite. Dark coloured schlieren at the contact with limestones are enriched in Mn and Fe. The grain-size distribution is unsorted with relatively normal distribution; (2) *variegated weathering products* in the central depression are composed of quartz, locally feldspars, muscovite, biotite, kaolinite and accesoric illite-miontmorillonite and montmorillonite. Dominant content of kaolinite was not proved. Heavy minerals consist of instabile minerals (pyrite, epidote, etc.) and locally increased content of chemostable minerals (garnet). The content of *in situ* weathered clasts of gneisses is remarkable. The grain-size distribution is unsorted, curves are platycurtic and the assymetry is relatively normal, and (3) *fillings of small pockets* are composed of dominant quartz and feldspars, locally muscovite and rarely chlorite, lesser amounts of vermiculite, and sepiolite. Heavy minerals are typical by relatively high percentage of mechanostable minerals and distinct content of chemostable minerals. The grain-size distribution is unsorted, curves are highly leptocurtic.

Variegated weathering products are the oldest generation of the fill. Previous authors described them as the relics of tropical weathering. Nevertheless, the kaolinite content is relatively low. Also the character of heavy mineral assemblages is not mature with prevailing instabile forms. It seems, that such deposits cannot be characterized as mature kaolinic deposits as they contain also high percentage of fresh feldspars, muscovite and even biotite. The character of deposits and their mineralogical composition indicate that these light-coloured weathering products were not transported or that the weathering took places only after the transport of primary mechanical weathering products, i.e. they are *in situ* weathered.

The second generation of the fill is reprezented by lithologically variable sediments among karst cones. They partially cover the first sediment generation. Important is the higher content of sepiolite formed by the authigenic crystallization from water solutions (Stoch 1974) and contents of muscovite and vermiculite-chlorite. Sediment structures indicate the origin from slope deposits sunken into developing karst forms.

The last generation of the fill are sandy deposits in small pockets of fluvial origin (higher terrace of the Morava River).

The geomorphology. The transversal section through the Morava valley indicate the presence of broad paleovalley at 1 100 to 1 200 m a.s.l. and the presence of several slope steps within the slope (at 970, 870 and 850 m a.s.l.). Correlate sediments in adjacent regions are occurring at 840 to 860 m a.s.l. They are relatively rare and they are of the Neogene age. They were constituents of pre-Badenian river network (Malkovsky 1975, 1979) differing in the organization from post-Badenian river network which originated after uplift of the eastern margins of the Bohemian Massif caused by the young Styrian phase of the Alpine Orogeny. The river network on the Polish part of the Snezník Mt. had also the complex history. Walczak (in Bosák and Hysek 1994b) expected, that the valley of the Nysa River is early Tertiary and the valley of the Biala Ladecka River is at least of Miocene age.

To assume the evolution of the river network and of geomorphic forms in the area studied, there could be taken into the account the general evolution of eastern margins of the Bohemian Massif after the upper Cretaceous regression. The existence of deep pre-Miocene valley forms was proved. In the eastern slopes of the Massif they attain the depth of about 1 000 m (Zeman 1980) and were filled by Paleocene/Oligocene-Miocene sediments. Valleys started to form even during lower Cretaceous and were partly flooded by Albial ingression. During the Oligocene, the base level was therefore situated at the level -1 000 m in the Carpathian Foredeep. This intensive lowering of the base level and deep entrenchment caused rapid backward erosion and the evolution of diversified river valley network. Its parts are now filled with marine sediments of the lower Badenian (Moravian) in the Moravian, Tisnov and Hranice Karsts and also in non karst regions deeply to the northwest. In other places, valleys are filled by the continental equivalents (*cf.* Prosová 1974). The entrenchment of deep valley was simultaneous with the uplift of marginal mountain range of the Massif which enhanced the extent of deep and backward erosion.

The second important stage of the evolution was the Messinian stage of deep lowering of the base level. The lowering of the Black sea level reached -1 600 m (*cf.* Hsü and Giovanelli 1979) as compared with the recent situation. This sea level drop was reflected in increased rate of erosion and in rapid progradation of backward erosion in the foreland. This stage of river-affected morphogeny was proved by Glazek (1989a) in Polish High Tatra Mts.

Discussion. Comparing the geomorphological form of the area studied with above mentioned data, it seems that the pre-Badenian stage of morphogeny is imprinted in altitudes above 950 m a.s.l. Inserted "terrace" steps in valley slopes can be attributed to rests of pediments in accordance to Walczak (in Bosák and Hysek 1994b). The rest of the valley, except the sharp entrenchment in the bottom (40 m) is supposedly of pre-Pliocene age. The entrenchment has been dated by several authors to post-Miocene erosion reflecting the mountain uplift (e.g. Madera 1983). Relative position of summits of karst cones in the Mramorovy Quarry is now 40 to 120 m above the river bed. Nevertheless, the whole situation is complicated by neotectonic movements along transversal faults which caused e.g. the cut of cave paleodrainage routes (*cf.* Madera 1983).

The data mentioned above indicate that limestone strips were uncovered due to deep and backward erosion. With any doubts, the lowest entrenchment in the valley can be correlated with the period of youngest evolution, i.e. to the period after the dissection of pre-Badenian paleoriver network (uplift). This phase is dated to Pliocene-Quaternary, as movements (uplift) was connected with the young Styrian phase of the Alpine Orogeny (upper Badenian to Sarmatian, Roth 1980).

Paleoclimates in that time were characterized by the termination of tropical climatic types after the lower Sarmatian age (Gregor 1980). Climate changed, precipitations and temperatures droped (Sinicyn 1980). The Pliocene was already characterized by climatic oscillation of the glacial type (Frakes 1979).

The remaining problem represents the datation of the narrow, 40 m deep entrenchment of the river valley which is connected with the restoration of river network and with young piracy processes. It could be supposed, that the whole valley (except the entrenchment) was created even during the Messinian (the end of Miocene) and that the entrenchment is younger (Plio)-Pleistocene. Nevertheless, the evolution stages are not correctly dared and represent only the working hypothesis.

Model. The model of origin of covered karst in the Mramorovy Quarry is based on above mentioned data and hypothesis, i.e. on the assumption that the valley was finished at the end of Miocene (Messinian). Two basic evolution stages can be distinguished. The *older phase* caused the deep karstification of limestones along longitudinal fault structures. They are distictly older than transversal faults without traces on neotectonic movement. This karstification can be correlated with pre-Messinian stage. Light-coloured weathering products with red clays at the base, limonitic layers and caves with limonites at -100 m originated in this stage. The low kaolinite content and heavy mineral assemblages indicate lower intensity of weathering processes or that weathering took place only for a short period. This fact be connected with the upper Miocene climate. Weathering products sunk into the forming depression and here were *in situ* weathered. The *younger phase* can be connected with younger, Quaternary, geomorphic processes, i.e. with the Morava River entrechments due to the uplift of the mount. Conical-shaped karst forms originated during strong corrosion by aggressive waters from thawing of icefields or firn during the interglacial periods. Resulting form can be compared with the clint-and-grike morphology. It originated beneath the sedimentary cover composed by fresh (not mature) weathetring products of the till-type. Based on the presence of sepiolite, they were deposited in water environment and gradually sunk into depressions. Karst forms therefore represent the covered karst (*sensu* Bosák, Ford and Glazek 1989) or screened karst (of Tsykin 1989). Zones enriched in Mn and Fe encircling karst cones and impregnating certain horizons in sediments precipitated from percolating solutions probably of river origin (*cf*. Ford and Williams 1989). The connection with the entrenched lowest part of the valley is clearly reflected in decreasing altitude of karren cones upslope. All the forms and sediments were later covered by two solifluction horizons. This indicates that the evolution and filling of the karren topography finished before last glacial at least.

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