

## Chapter 1.4

### THE TYPOLOGY OF GYPSUM KARST

#### ACCORDING TO ITS GEOLOGICAL AND GEOMORPHOLOGICAL EVOLUTION

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"The interaction of limestone and aggressive water ... creates an unique landform known as karst."  
(Dreybrodt, 1988)

"Karst is a landscape formed upon and within carbonate rock sequences by the dissolutional effect of carbonic acid" (Lowe, 1992)

"Karst is primarily a landscape, with specific landforms and solution features, which are mainly developed in carbonate rocks" (EUR 16526, 1995)

#### 1. Introduction: Gypsum karst - a true karst!

It is commonly believed, as demonstrated by the quotations above, that the term karst applies implicitly and exclusively to phenomena in carbonate rocks. Such views can be explained, although not necessarily justified, by examination of the history of karst studies, which developed originally within limestone areas. Some early researchers, such as Martel, defined karst as phenomena in limestones. Some modern researchers argue that only chemical dissolutional mechanisms, like carbonic acid dissolution of carbonates, can be regarded as producing a true karst. Cigna (1978, 1985) suggested use of the term parakarst (the prefix para- implies something that is similar to the parent word, but not a "true" synonym) for karst phenomena developed in gypsum (two components in phase equilibrium). This contrasts with true karst (karst *sensu stricto*; comprising three components). Such usage is adopted in the official Speleological Subject classification of the UIS. Lowe (1992), having stated a similar viewpoint, referred to terms such as evaporite karst (including halite, gypsum and anhydrite karsts) as hybrid terminology. The same understanding of karst, as including only phenomena in carbonate rocks, is tacitly implied, though not always directly stated, by many other workers.

Such views can be disputed, however, and are argued against here. For historical background it is worthwhile to quote Jakucs' thought, "...from today's viewpoint it is unsatisfactory to regard the reference to the semantic origin of the term as correct conceptual definition of the karst in general" (1977, p.15). The definition of a natural system should be derived from its own properties but not from the properties of its components. Karst phenomena belong to a geological-geographical level of the organization of matter, not to a physical-chemical one. Specific features of rock permeability, hydrogeology, hydrography and geomorphology of terrains, developed due to dissolution (regardless of its exact mechanism and number of components in phase equilibrium) are essentially the same in the various lithologies that are readily soluble under natural conditions. This point is illustrated clearly by the entire content of this volume.

Before making any attempt to categorize gypsum karst, the general meaning of the term karst itself should be clarified further.

## 2. Definition of karst

The origin of the term karst and the history of karstological studies led to karst being treated most commonly as a specific landscape or terrain, with distinctive hydrology and landforms (e.g. Jennings, 1985; White, 1988; Ford & Williams, 1989; Lowe, 1992; EUR 16526, 1995). Most karstological and speleogenetic ideas and theories are concerned with unconfined karst settings and ultimately they imply close hydrological and morphogenetic relationships between the surface and the subsurface. Strictly, such definitions, and the whole traditional karst paradigm, either ignore deep-seated karst that has no apparent relationship with the visible landscape, or treat such features as palaeokarst. Some authors distinguish a special category of intrastratal karst, formed within rocks already buried by younger strata, where karstification is younger than the cover (Quinlan, 1978; Palmer & Palmer, 1989; Bosak, Ford & Glazek, 1989). The latter two works emphasize that abundant modern (active) intrastratal karstification is in progress. Confined (or artesian) karst falls within this category, but the whole concept of intrastratal karst, as well as of artesian karst, seems not to be an essential part of the traditional karstological paradigm.

The term "karst" is also used to describe particular landforms and subsurface features produced by a specific set of processes in which dissolution is the main one, initiating or triggering other processes such as erosion, collapse and subsidence (Quinlan, 1978; Milanovic, 1981; Bonacci, 1987; James & Choquette, 1988). This allows deep-seated dissolution features to be referred to as karst, but does not resolve the general conceptual problem.

An approach long accepted in the Soviet Union was to regard karst as a process, or an amalgam of process and resulting phenomena. In western literature, Huntoon (1995) discussed a need for a process-oriented definition of karst, to emphasize its hydrological function and geohydrological uniqueness, rather than dwelling upon its ambiguous morphological character.

To distinguish between elementary processes or forms, and karst as a typologic category, it is necessary to adopt the system approach, and emphasize the system-forming properties. The author tends to view karst as a specific mass-transfer system within the Earth's crust. To emphasize particular system-forming properties, the most appropriate definition seems to be that suggested recently by Huntoon (1995), which is adopted here in modified form (Huntoon originally defined karst as a geological environment):

Karst is a mass-transfer system containing soluble rocks with a permeability structure dominated by interconnected conduits dissolved from the host rock that are organized to facilitate the circulation of fluid in the downgradient direction wherein the permeability structure evolved as a consequence of dissolution by the fluid.

This definition allows reference to karst phenomena (features or forms), as well as to karst processes, as to components of a system, although the mere action of a certain elementary process (e.g. dissolution), or the presence of a certain morphological feature (e.g. any dissolutional sculpting or a void) would not in itself imply the existence of a system as required by the defini-

tion. The definition does not require that the rocks have a specific lithology, nor is a specific dissolutional mechanism called for and the circulating fluid is not limited to water. It is sufficiently broad to encompass circulation systems in unconfined and confined settings, in the shallow sub-surface and in deep-seated environments. The question of whether karst is expressed at the surface or not is irrelevant.

### **3. Karst evolution: general approach**

Stratigraphical position of karst, the question of whether and how karst is related to the surface and, eventually, the whole problem of karst typology are clearly all aspects of the general problem of karst evolution, or its development through geological time. Many terms describe these aspects, commonly with conflicting meanings and confusing usage, as was demonstrated clearly by Bosak, Ford & Glazek (1989), who reviewed interrelated conceptual and terminological problems in the most logical way. The discussion they provided and the definitions they suggested are taken as starting points for the following consideration.

A common belief among karstologists is that karstification is ultimately related to the surface. Hence, it generally starts or is re-activated when uplift results in partial or total exposure of a formation. Such a view is perfectly natural within the dominant geomorphological paradigm of karstology, and is implied by terms such as buried karst, covered karst, exumed karst, as well as by the whole concept of palaeokarst. The concept of intratratral karst stands apart from this view, as some authors have allowed for deep-seated karst development (Quinlan, 1978; Bosak, Ford & Glazek, 1989; Palmer & Palmer, 1989). These and other related terms are considered and re-stated below. The present author argues that karst develops widely in deep-seated, confined settings, with no apparent relation to the surface (Klimchouk, 1997); similar views were expressed by Lowe (1992). Subsequent elevation of karst into the shallow sub-surface might best be considered as a certain evolutionary stage within the normal sequence of a deposition-burial-uplift-erosion cycle, rather than the shallow sub-surface being viewed as the ultimate karst-forming environment.

At the core of the definition of karst adopted above is the concept of an organized permeability structure, evolved as a result of dissolution. In terms of evolution, there may be progressive development (creation/construction dominates) or regressive development (destruction dominates). Karstification applies to progressive development.

Karstification can commence immediately after sedimentation and proceed through the whole geological history of a formation. Potentially it includes deep-seated (buried) and exposed stages, which eventually contribute to the complete disintegration and removal of the rock. However, before the system-forming requirements are fully met, initiation, or inception, processes not necessarily encompassed within the karst system as defined above, must begin. Although complete karst (in the system sense) can develop in deep-seated settings, in many cases it occurs only in the near-surface environment, where hydraulic gradients that drive circulation are maximized. To some extent this explains an apparent bias of karstological studies and theories towards unconfined settings and exposed karsts. Another, basically "anthropocentric", reason relates merely to the fact that near-surface karst is most easily recognizable.

During a period of karstification distinct phases may be characterized by a particular activity of

the process. Phases are characterized by particular hydrogeological settings, to which developing karst features tend to adjust. Such phases are individualized by unique combinations of geodynamic or climatic changes that result in new conditions becoming established. Karst system components formed during a previous phase may become relict, or may be inherited by the new structure, developing in adjustment with the new settings.

Karstification can be interrupted by regressive development phases, when destruction of karst permeability predominates over its creation. Bosak (1989) examined causes and conditions for fossilization of karst. Karst becomes fossil or inactive when it loses its hydrological function, so that any pre-existing fluid circulation system is seriously interrupted and eventually destroyed. Change of phases within a single karstification period, as outlined above (without significant interruption of karst development), may result in similar fossilization effects, though these encompass only some components, and not the entire system.

The term palaeokarst is probably best used in the broad sense outlined by Jennings (1985) and re-stated here: to comprise morphological or geological features of a karst system that are of considerable age and are not adjusted to the present dynamic controlling factors. Such factors comprise flow conditions and architecture. Loss of hydrological function within a system is generally caused by regional changes of geotectonic conditions, or by global sea level variation (Bosak, 1989). As such changes normally encompass extensive timespans, the formal definition of palaeokarst given in Bosak, Ford & Glazek (1989) is also appropriate in most of cases: "...palaeokarst refers to karst developed largely or entirely during past geological periods". In the light of the karst concept outlined above, the deep-seated occurrence of karst cannot serve alone as a criterion to identify palaeokarst, as is still widely implied.

#### **4. Types of karst according to its evolution and stratigraphical position, with special reference to gypsum karst**

An idea that typology of karst according to its stratigraphical position, or to the presence of cover beds, should bear an evolutionary meaning, was outlined most clearly by the Soviet karstologist Ivanov (1956). He distinguished covered, semi-covered and open stages of karst development, a succession that represented the main evolutionary trend during the neotectonic epoch. Considering the above discussion, the following general sequence of evolutionary types (stages) of karst can be outlined (Fig. 1): sub-syn depositional karst - intrastratal karst - exposed karst - covered karst - buried karst - exhumed karst.

As was stated above, karstification can begin immediately after sedimentation. It is shown (Gunn & Lowe, in press) in the tropics, karst does form on recent carbonates in the littoral environment, and such features may survive gentle uplift or more extreme tectonism. Karst is widely known in coastal and oceanic environments, in older carbonates that never experienced burial (see recent summary by Mylroie & Carew, in press). As for sulphates, some dissolutional sculpting phenomena are known to develop during wet seasons on the surface of recently deposited sediments in some modern evaporate basins, such as lakes in the Qinghai-Xizang Plateau, China (Yaoru & Cooper, this volume) or the Kara-Bogaz-Gol lagoon in the Caspian Basin of

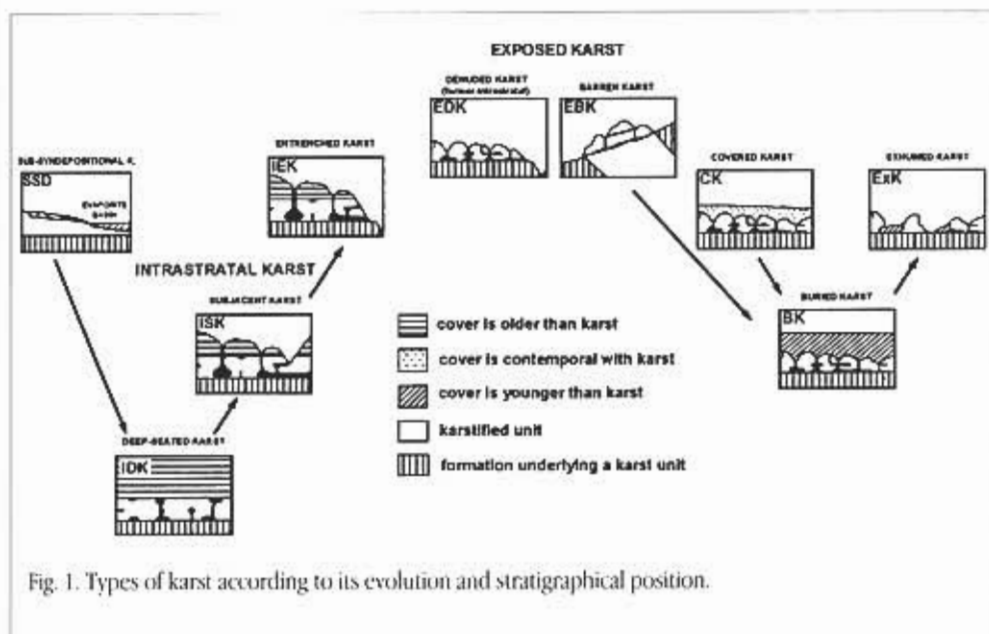


Fig. 1. Types of karst according to its evolution and stratigraphical position.

Turkmenistan. Such features are ephemeral and do not form a karst system as defined above. However, in the vicinity of some drying lakes in China, extensive layered Pleistocene gypsum deposits exhibit features such as corroded flutes, fissures and small caves (Yaoru & Cooper), which can be said to comprise a shallow karst circulation system. A sub-syn depositional karst type is distinguished here to encompass such cases. The extent of this type of karst is currently small, but the type could be more common during major epochs of halogenesis. Being fossilized by subsequent burial, karst and diagenetic features formed during the sub-syn depositional stage can influence later karst development.

It is much more common, however, for sulphate formations to be buried after deposition. It is argued here that the full development of gypsum karst can occur widely in deep-seated settings, particularly when differential uplift imposes significant hydraulic head gradients across a basin (Klimchouk, 1997).

The evolutionary sequence of karst types outlined above is rarely continuous for a particular karst. For instance a karst system may develop largely at the intrastratal stage, or at the exposed stage. Gypsum karst may be completely disintegrated, along with its host formation, within the same stage that its development occurred, so that gypsum karst can hardly survive through more than one burial-exposure cycle. In general, it appears that the gypsum karst life cycle is commonly shorter than that of carbonate karst, but actual evolution depends greatly upon the geological history of the particular region.

### 4.1. Intrastratal karst

Quinlan (1978) originally distinguished interstratal karst, which develops beneath rocks or sediment that were deposited before karstification. Palmer & Palmer (1989) suggested that the term intrastratal karst is more appropriate, as most dissolutional processes at depth are not limited to boundaries between strata. Following the above authors, intrastratal karst is defined here as karst that is formed largely by deep-seated processes, within rocks already buried by younger strata, where karstification is later than deposition of the cover rocks.

Gypsum outcrops at the surface cover only quite small areas, but the extent of territories where sulphate rocks exist at depth is great. Ford & Williams (1979) estimated that gypsum and/or salt underlie about 25% of the continental surfaces. This figure gives an indication that the potential area for intrastratal gypsum karst development is comparable in extent with that of carbonate karst. (It is likely that intrastratal karst is also the most common type of carbonate karst; a possibility that has been obscured both by the prevalence of the geomorphological concept of karst and by the limited recognition of deep-seated karst in general).

There is much evidence of well-developed conduit porosity and groundwater circulation through gypsum formations at depths up to several hundred metres, or locally more than 1000m. Gypsum and anhydrite are commonly intercalated with dolomite and limestone beds, and/or associated with salt sequences. Karst develops mainly under confined conditions. Gypsum layers are normally underlain and overlain by porous or fissured aquifers, and the gypsum beds serve as aquicludes rather than aquifers during the initial stages of karst development. Dissolution generally focuses along the lower and upper contacts, although speleogenetic development within gypsum sequences also follows tectonic faults, or is dispersed via uniform lithogenetic fissuring. This results in full hydraulic communication being established through the gypsum and into adjacent aquifers. (See Chapters 1.5 & 1.6 for more details of hydrogeology.) Such development is activated, particularly beneath large valleys, if continuing uplift brings a formation into a shallower position. Under deep-seated conditions, intrastratal karst can develop without any surface expression, although dissolution of gypsum strata commonly induces the breakdown processes that affect cover beds. Characteristic features associated with intrastratal gypsum karst are breccia pipes, which propagate upwards through the cover rocks for many tens, or even hundreds, of metres. Surface karst landscapes can begin to evolve when the cover thickness becomes less than 50-90m (see Chapter 1.10). There are abundant well-documented examples of intrastratal gypsum karst in many European countries, in Siberia, in China and in North America.

Intrastratal karst can be subdivided into deep-seated karst (which is not evident at the surface; Fig. 1-IDK), subjacent karst (which is evident at the surface but is not deeply entrenched by erosional valleys; Fig. 1-ISK) and entrenched karst (where the whole or the greater part of the thickness is entrenched and drained by valleys; Fig. 1-IEK). Deep-seated intrastratal karst passes into subjacent karst, and then into entrenched karst, in response to continuing uplift, denudational surface lowering and fluvial incision. However, the karst remains within the intrastratal category while the original cover beds remain largely unstripped by denudation. The best documented example of intrastratal gypsum karst is that in the Western Ukraine, where all three subtypes are represented in succession across the region due to differentiated uplift (see section 4.6 and Chapter II.9).



Buried gypsum sequences can be entirely removed by dissolution before they achieve exposure. Such dissolutional removal leaves characteristic karst breccias (sometimes termed pseudobreccias) composed of insoluble or less soluble remnants of any intercalated beds (commonly carbonates) and broken fragments of the overlying rocks.

## 4.2. Exposed karst

Areally uniform denudational surface lowering and removal of formations overlying subjacent karst causes increased exposure of karstifiable rocks at the surface. When the area of fully exposed karstifiable rocks becomes dominant over the area of remaining caprock, the karst can be considered exposed. Direct exposure of gypsum surfaces to aggressive meteoric waters gives rise to a great variety of dissolutionally sculpted landforms, due to high gypsum solubility and fast dissolution kinetics. These aspects are discussed in Chapter 1.8. Landform assemblages and their distribution, which develop in response to underground karstification, are different for the two principal subtypes of exposed gypsum karst outlined below.

A denuded karst category (a subtype of exposed karst) was distinguished by Quinlan (1978) to identify former intrastratal (subjacent or entrenched) karst that is exposed by erosion of its cover. This understanding is adopted here (Fig. 1-EDK). Denuded karst is characterized by the co-existence of karst features formed during the exposed stage and those inherited from previous stages. The latter are largely relict, but are partially adjusted to the new hydrological and hydrogeological setting. Inherited subsurface karst features greatly influence the development of karst landscape and hydrology. Already existing conduit permeability induces collapse forms etc, so that the karst landscape develops largely as a "reflection" of the existing structure of the underground karst. Denuded gypsum karsts commonly present complicated polygenetic cavity systems and an exceptionally high density of dolines or open pits at the surface. Well documented examples occur in the north of the East-European platform and the Urals in Russia, and in some mountain areas of Central Asia.

Barren karst is a subtype of exposed karst that develops largely during the exposure stage, either where karstifiable rocks have not undergone significant karstification before exposure, or where previously developed karst features have been completely fossilized and not rejuvenated at the exposure stage. Such a karst represents the "pure line" of development, solely controlled by surface and shallow subsurface factors (Fig. 1-EBK). A peculiar feature of some barren gypsum karsts is that rocks exposed to the action of surface agents experience late diagenetic (catagenetic) transformations, such as contraction, re-crystallization, expansion due to the volume increase, and so on. These processes affect the outer layer of gypsum, resulting in the formation of specific contraction-expansion features, or a crust that seals fissures in the outer layer (for details see chapters 1.2 and 1.9). Macaluso & Sauro (this volume) treat such effects as a specific type of gypsum rock weathering. These phenomena are best expressed in some arid areas, such as Sicily, but whether climate is the decisive factor remains unclear. It is likely that local peculiarities of geological setting and paleogeographical history (for example, how well the gypsum was "protected" from transformations during preceding burial, or how rapidly the formation was exposed) determine the

extent to which these phenomena are expressed.

The best known examples of barren gypsum karst are from the Sicily and Emilia-Romagna regions in Italy (Chapter II.8). Some features that could be interpreted as palaeokarst, are completely fossilized and have not affected recent karst development. Barren gypsum karsts in Italy are characterized by a relative scarcity of dolines and an absence of dispersed recharge from the surface (epikarst does not develop). Caves tend to be linear, directly connecting points of localized recharge and resurgences. Surface sinkholes and caves are guided by faults and other major tectonic fissures, whose distribution is highly heterogeneous and anisotropic. Circulation systems tend to be shallow.

Some exposed gypsum karsts have characteristics that differ from those described above. However, it is not quite clear whether such cases represent true barren karst systems or if they fall into the denuded karst category, with their structure of karstification inherited to a considerable degree from previous stages.

#### **4.3. Covered karst**

This term is used here in the narrow sense outlined by Tsykin (1989). It specifies karst formed where an autochthonous cover has developed syngenetically and contemporaneously with exposed karstification (Fig. 1-CK). Sulphate formations leave little insoluble residue, however they commonly include carbonate and clayey intercalations. Where active karstification occurs in the exposed settings, these less soluble, or insoluble, materials remain at the surface when gypsum is removed, forming a kind of breccia-like cover. This is illustrated by some gypsum karst areas in the pre-Ural region, Russia, where the still remaining sulphate sequence is covered by the 5-50m thick mantle of residual breccia (see Chapter II.11).

#### **4.4. Buried karst**

The most widely accepted meaning of the term is adopted here. It is defined as karst that was covered by later rocks, after having first undergone some exposed development. Most gypsum karsts that survive the intrastratal stage disintegrate during the exposure stage, along with their host formations, due to the high solubility of gypsum and its fast dissolution kinetics. The same holds true for barren gypsum karsts, where development began only when the rocks became exposed. This explains why buried gypsum karst is uncommon. Cooper (this volume) describes an example in the Vale of Eden, Cumbria (United Kingdom), where glacial till and sand/gravel deposits conceal and partly infill a buried karst with pinnacles, in the "B" bed of the Permian gypsum. Karst features here pre-date the last glaciation, and caves are assumed to have formed partly as a sub-glacial phenomenon under increased hydrostatic head. Another example from the UK is a case of rarely documented recent burial in the marine environment. Late Permian gypsum and anhydrite crop out beneath 10-20m of Quaternary cover on the bed of the Firth of Forth and the North Sea, some 90km east of Edinburgh. Shallow seismic survey produced an image of the rock surface, which appears to include pinnacles surrounded by foundered Triassic strata (Chapter II.3). In the Pinego-Severodvinsky region on the north of Russia buried gypsum karst is



evidenced by the presence of dolines filled with marine boreal sediments. In the Pre-Ural region some large depressions filled with Neogene sediments are associated with some ancient stage of karstification, probably Mesozoic (Chapter II.11).

#### 4.5. Exumed karst

This term describes karst that has been exposed by erosional removal of cover rocks that had once buried it (Quinlan, 1978; Bosak, Ford & Glazek, 1989). The present author is unaware of any examples of gypsum karst of this type.

#### 4.6. Succession of the evolutionary types of karst

In some regions differential uplift or monoclinial occurrences of gypsiferous sequences result in differential stripping of the formations that overlie intrastratal karst. In these situations a progression of karst types is represented across the region.

In the Western Ukraine there is an extensive Miocene gypsum sequence on the edge of the East-European platform (for details see Chapter II.9). It was overlain by the argillaceous carbonate and clay sediments, and intrastratal karst was developed under artesian conditions. Three stages of gypsum karst development are currently distinguished here, each representing some type of karst outlined above.

1. Recent (modern) artesian settings still exist within the submerged outskirts of the platform, along its boundary with the Carpathian foredeep. Many caves have been intersected by boreholes, especially in the vicinity of the buried valleys that are known here. Superficial karst forms are absent in areas where the thickness of cover beds exceeds 50-70m. A belt of deep-seated intrastratal karst borders the external boundary of the foredeep.

2. Toward the interior of the platform the cover bed thickness decreases, so that collapse-breccia pipes that develop upwards from the gypsum sequence reach the surface. Initial collapse forms are reworked rapidly into cone-shaped dolines, commonly containing swallow-holes (ponors). Moreover, some erosional valleys become sufficiently entrenched to breach artesian confinement, or even to cut through parts of the gypsum sequence, causing the potentiometric surface to drop beneath its top. Typically karstic hydrographic features evolve, including rising karst springs, blind valleys with disappearing streams, and karst lakes in large dolines or depressions. Inflow and outflow caves are common. Upper storeys of multi-storey cave systems become locally accessible, while their lower passages remain water-filled. The belt that includes these features represents intrastratal adjacent karst.

3. Further still towards the platform interiors intense uplift during Pleistocene times caused major river valleys to entrench well below the base of the gypsum succession, though the clay cover beds survive across most of the inter-valley plateau areas. Extensive maze cave systems became wholly drained and relict. Vertical pipes have formed in the gypsum where downward percolation occasionally focuses, causing upward stoping through the cover beds. Swallow-holes and dolines evolve at the surface as a result. In places linear vadose caves develop from swallow-holes towards neighbouring valleys. This situation represents intrastratal entrenched karst.

In the Vale of Eden, in northwest England, differential geomorphological evolution and a

monoclinical structure have imposed a succession of karst types across the widespread Permian "B" bed gypsum, passing from one to another along the west to east stratal dip (Cooper, this volume). An area of complete gypsum dissolution passes into buried gypsum karst with pinnacles (formerly a denuded karst in pre-glacial times), next into intrastratal entrenched karst with caves, then into massive gypsum (subjacent karst?) and finally into massive anhydrite (deep-seated karst?).

## 5. Palaeokarst

The term palaeokarst does not represent a particular type of karst, but refers to a specific - fossilised - state of a karst. Karst is defined (see above for the full definition) as a system that provides mass transport through rocks with an organized permeability structure that evolved as a consequence of dissolution by fluid. Hence, a palaeo-system is karst that lost its mass transport function. In contrast to active karst, palaeokarst does not describe a combination of processes and phenomena, but merely phenomena: including forms and/or sediments. The ultimate result of karst development can be that a karstifiable sequence is entirely removed (dissolved), being replaced in the geological cross-section by residual sediments and/or sediments that were emplaced within now-disappeared karst forms during karstification. This means that palaeokarst can be recognized even when the host rock no longer exists. This point is of particular importance for intrastratal gypsum karst.

Ford & Williams (1989) stressed that palaeokarst features should be considered hydrologically decoupled from contemporary systems, in contrast to relict features, which exist within contemporary systems but are removed from the environment in which they developed.

Karst systems, or their components, can be fossilized at any of the karst development stages specified above. It may occur inevitably when sub-syn depositional karst is buried. Deep intrastratal gypsum karst can develop fully and then disintegrate, possibly to the extent of total removal of gypsum beds from a cross-section, without having been elevated to the shallow subsurface. Characteristic horizons of karst breccia (composed of minor insoluble intercalations and fragmented overlying rocks) are common within sulphate and sulphate-carbonate sequences, where they represent intrastratal palaeokarst. However, it is worth re-emphasizing that the occurrence of deep-seated karst does not, in isolation, indicate the existence of palaeokarst, as is implied by traditional geomorphological concepts of karst. Active karst development also occurs commonly in this environment, as it was clearly indicated by Palmer & Palmer (1989, p.337): "Intrastratal features are considered paleokarst only if they are out of adjustment with the present geologic setting. This criterion is often difficult to apply, for intrastratal processes tend to operate over a long time span, and many features that qualify as intrastratal paleokarst were formed by processes still operating at a diminished rate today." Moreover, even those intrastratal features that are filled with collapse-breccia are not necessarily palaeokarst. Confusing instances are breccia pipes, or columns, common features of upward stoping through overlying formations, induced by dissolution processes in underlying gypsum beds. As is shown in Chapter 1.10, breccia pipe development is not merely a breakdown process, but is maintained by active groundwater circulation through pipes, with partial mass-removal by dissolution. They become palaeokarst features only when they

are fossilized to the extent that groundwater circulation is interrupted.

Complete dissolution of gypsum beds can occur even more readily in subjacent gypsum karst, due to intense circulation of groundwaters. In fact, dissolution and removal of mass in solution are greatest in this environment (see Chapter I.3).

When karst passes into the entrenched stage, most previously formed conduits (artesian, phreatic, water-table) become relict, as circulation in the now dominant vadose zone is highly localized. Further evolution into exposed karst re-activates many relict features as they become increasingly integrated into a karst landscape where dissolution is more dispersed. However, this stage also favors the complete disintegration of a karst system by initial separation and eventual removal of the exposed gypsum sequence. When subsequent burial occurs, parts of a contemporary system can become separated hydrologically and become completely fossilized, so that buried karst is largely palaeokarst. In some situations such palaeokarst can be exhumed and re-integrated into active systems. However, as noted above, gypsiferous rocks rarely survive through the full succession of karst stages.

## References

- DREYBRODT, W. 1988. Processes in karst systems. Springer-Verlag: Berlin.
- BONACCI, O. 1987. Karst hydrology, with special reference to the Dinaric Karst. Springer-Verlag, New York: 184.
- BOSAK, P., FORD, D.C. & J. GLAZEK, 1989. Terminology. In: (P.BOSAK, D.FORD, J.GLAZEK & I.HORACEK, eds.): Paleokarst: a systematic and regional review. Academia, Praha: 25-32.
- BOSAK, P. 1989. Problems of the origin and fossilization of karst forms. In: (P.BOSAK, D.FORD, J.GLAZEK & I.HORACEK, eds.): Paleokarst: a systematic and regional review. Academia, Praha: 25-32.
- GUNN, J. & LOWE, D.J. In press. Speleogenesis on tectonically active carbonate islands. In: Speleogenesis: Evolution of karst aquifers.
- CIGNA, A. A. 1978. A classification of karstic phenomena. *Int. J. of Speleology*, 10 (1). 3-9.
- CIGNA, A. A. 1985. Some remarks on phase equilibria of evaporites and other karstifiable rocks. *Le Grotte d'Italia* (4) XXII, 1984-1985. 201-208.
- EUR 16526. Hydrogeological aspects of groundwater protection in karstic areas. Guidelines. Luxembourg: Office for Official Publications of the EC. 1995. 15 p.
- FORD, D.C. & WILLIAMS, P.W. 1989. Karst geomorphology and hydrology. London: Unwin Hyman, 601 p.
- HUNTOON, P.W. 1995. Is it appropriate to apply porous media groundwater circulation models to karstic aquifers? In: (ALY I. EL-KADI, ed.): Groundwater models for resources analysis and management. Lewis Publishers, Boca Raton: 339-358.
- JAKUCS, L. 1977. Morphogenetics of karst regions: variants of karst evolution. Budapest: Akademiai Kiado.
- JAMES, N.P. & P.W. CHOQUETTE (eds.). 1988. Paleokarst. Springer-Verlag, New York: 416.
- JENNINGS, J.N. 1985. Karst geomorphology. Basil Blackwell, Oxford: 293 p.
- IVANOV, B.N. 1956. On typology of karst landscapes of planes, on the example of Podol'sko-

- Bulovinsky karst region. In: Voprosy izuchenija karsta na jube Evropejskoj chasti SSSR. Yalta. 131-156.
- KLIMCHOUK, A.B. 1997. Artesian speleogenetic setting. Proc. 12th Internat. Congress of Speleology, La Chaux-de-Fonds, Switzerland.
- LOWE, D.J. 1992. The origin of limestone caverns: an inception horizon hypothesis. Ph.D. Thesis, Manchester Metropolitan University.
- MILANOVIC, P.T. 1981. Karst hydrology. Water Resources Publications, Littleton, CO: 434 p.
- MYLROIE, J. & CAREW, J. In press. Coastal and oceanic settings. In: Speleogenesis: Evolution of karst aquifers.
- QUINLAN, J.F. 1978. Types of karst, with emphasis on cover beds in their classification and development. PhD Thesis, Univ. of Texas at Austin.
- PALMER, M.V. & A.N. PALMER, 1989. Paleokarst of the United States. In: (P.BOSAK, D.FORD, J.GLAZEK & I.HORACEK, eds.): Paleokarst: a systematic and regional review. Academia, Praha: 337-365.
- TSYKIN, R.S. 1989. Paleokarst of the Union of Soviet Socialist Republic. In: (P.BOSAK, D.FORD, J.GLAZEK & I.HORACEK, eds.): Paleokarst: a systematic and regional review. Academia, Praha: 337-365.
- WHITE, W.B. 1988. Geomorphology and hydrology of karst terrains. New York: Oxford Univ. Press. 464 p.