Chapter I.1

SULPHATE ROCKS AS AN ARENA FOR KARST DEVELOPMENT

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The rocks in which karst systems develop are most commonly composed of carbonate, sulphate and chloride minerals. The sulphate minerals are quite numerous (see Table 1), but only gypsum and anhydrite form extensive masses in sedimentary sequences. Other minerals, which represent sulphates of K, Mg and Na, normally occur as minor beds (0.1-5.0 m), or as inclusions associated with chloride rocks. However, some minerals precipitated in salt-generating basins, such as mirabilite and glauberite (typically formed in the Kara-Bogaz-Gol Gulf, salt lakes of Siberia and in China), form sequences up to 5-10 m thick where karst may develop. Due to the very high solubility of Na -sulphates, karst processes and features occurring in these rocks resemble salt karst. Thus, the term sulphate karst, although not strictly correct, is used mainly to indicate karst developed in gypsum and anhydrite.

1. Gypsum and anhydrite

1.1. Minerals

Gypsum is a common mineral, known also by its chemical name of hydrated calcium sulphate: $CaSO_4 \times 2H_2O$. Chemically pure gypsum contains CaO - 32,5%, SO_3 - 46,51% and H_2O - 20,93%. Gypsum crystallises in the monoclinic system, forming tabular and prismatic crystals; cleavage is eminent along (010), perfect along (111) and (110); twins developed along (111) are common. The crystalline structure is layered, with layers of Ca^{2+} and SO_4^{2-} ions separated by water molecules. The mineral has a hardness of 2 and its density varies from 2.2 to 2.4 g/cm^3.

Gypsum may form as granular, laminated, powdered, fibrous and radiate-fibrous aggregates. In crystals gypsum is normally colorless and transparent, but it sometimes has brownish colours. Compact masses of gypsum may be white, gray, pink, red, brown, pale yellow or pale blue; sometimes the gypsum is dotted or marbly. Massive varieties of gypsum are known as alabaster, or sugar-like gypsum; fibrous varieties are referred to as satin spar. The term "selenite" can be confusing since it applies to fibrous gypsum in Russian literature, but is restricted to large tabular monocrystals of gypsum in English terminology.

Anhydrite is the anhydrous form of calcium sulphate, $CaSO_4$. Chemically pure anhydrite is CaO - 41,2%, SO_3 - 53,8%. Anhydrite crystals are rhombic with perfect cleavage along three orthogonal directions producing rectangular crystals. The hardness is 3.0 to 3.5, and its density varies from 2.863 to 3.10 g/cm^3.

Anhydrite commonly forms very compact fine-grained masses, but It also occurs as tabular, prismatic and fibrous aggregates. Common colours are white or pale shades of grey, blue, green, yellow, and red-brown.

Table 1

Principal rock-forming sulphate minerals of evaporite formations
(After Zharkova, 1981)

Sub-class	Mineral		Formula
Na - sulphates	Tenardite		Na_2SO_4
	Mirabilite		$Na_2SO_4 x 10H_2O$
	Glauberite		$Na_2SO_4 x CaSO_4$
	Vantgoffite		$3Na_2SO_4 x MgSO_4$
	Leoveite		$Na_2SO_4 x MgSO_4 x 2H_2O$
	Astrakhanite		$Na_2SO_4 x MgSO_4 x 4H_2O$
K - sulphates	K_1 - sulphates	Glaserite	$(K,Na)_2SO_4$
		Gergeite	$K_2SO_4 x 5CaSO_4$
		Langbeinite	$K_2SO_4 x 2MgSO_4$
		Shenite	$K_2SO_4 x MgSO_4 x 7H_2O$
		Polygalite	$K_2SO_4 x MgSO_4 x 7CaSO_4 x 2H_2O$
	K_2 - sulphates	Kainite	$KCl x MgSO_4 x 3H_2O$
Ca - sulphates	Anhydrite		$CaSO_4$
	Gypsum		$CaSO_4 x 2H_2O$
Mg - sulphates	Kiserite		$MgSO_4 x H_2O$
	Epsomite		$MgSO_4 x 7H_2O$

K_1-sulphates: without additional anions, K_2-sulphate: with additional anion.

1.2. Rocks

Calcium sulphate rocks can be represented by gypsum, anhydrite, or varying proportions of both minerals. Mixed rocks are called gypsiferous anhydrite or anhydritic-gypsum if the content of minor mineral is considerable. Sulphate rocks may contain, admixtures of clayey materials, carbonates and grains of sand; however, their purity is commonly high with the content of $CaSO_4$ (or $CaSO_4$ x $2H_2O$) varying between 95.0 and 99.5 %.

Gypsum rocks can be formed in different environments. The genetic classification according to Vikulova (date) is:

Primary deposits: I - lagoon deposits, formed due to evaporation of marine brines; II - continental deposits, (1) formed by evaporation in inland basins, (2) formed at the surface (2).

Secondary deposits (all continental): I - re-deposited; II - metasomatic:(1) formed by gypsum replacement of carbonates due to reactions with sulphuric-acid groundwaters; (2), formed by the action on limestones of sulphuric springs or volcanic agents; III - caprock deposits in salt diapirs; IV - "weathering" deposits formed by the hydration of anhydrite.

The most common are primary gypsum deposits and "weathering" deposits where anhydrite has re-hydrated to gypsum.

1.3. Formation

Most gypsum and anhydrite rocks have originated as evaporitic formations in marine (lagoon) and epicontinental sea environments. However, in some evaporite formations potassium or natrium salts are dominant. Within evaporitic marine basins, gypsum commonly precipitates on shoals and shelves, with halite in the deeps; highly soluble K-Mg- or Ca-Mg-chlorides preferentially on the western flank (Sonnenfeld, 1992). Gypsum and/or anhydrite sequences are commonly associated with beds and formations composed of carbonate and terrigenous sedimentary rocks.

Evaporite formations occur both in marine and continental sedimentary sequences. Marine evaporitic sequences are commonly associated with carbonates, but clays, siltstones and sandstones are also common. In continental sequences the most common associations are sands, sandstones, clays, shales, evaporitic dolomites and limestones. Based on evaporite and surrounding sediment associations, Krumbein (1952) distinguished four types of sequences; 1, alternating marine and lagoonal sedimentary sequences, where evaporites are associated mainly with carbonates; 2, evaporite accumulations suppressed by large inputs of continental terrigenous material; 3, successions which begin with a continental sedimentary environment and continue through lagoonal to marine environments; 4. evaporite formations within continental sequences.

Gypsum and anhydrite can occur as single beds, but they more typically occur as a series of beds intercalated with other sedimentary rocks. A good example of an extensive single bed is the 10-40 m thick Miocene gypsum in the Western Ukraine. The thickness of individual sulphate beds commonly ranges from several meters to several tens of meters, sometimes reaching several hundred meters, in units such as the Castile Formation of the Delaware Basin, southwest USA. Here the succession of evaporites (gypsum/ anhydrite and salts) in the Castile, Salado and Rustler Formations reaches 1,500 m in thickness (Chapter II.2 in this volume). Sulphates can also comprise some isolated minor beds within otherwise carbonate sequences. In most cases, gypsum and anhydrite beds, or formations, have distinct lithological boundaries with the over- and under-lying sediments, and form continuous spreads through quite extensive areas. The abrupt termination of sulphate beds commonly signifies either truncation by tectonic faults or dissolutional removal, either recent or ancient.

1.4. Gypsum-anhydrite-gypsum conversions

The stability of gypsum and anhydrite are considerably affected by changes in the physical and chemical parameters occurring within common geological environments. This results in back and forth conversions between these minerals. The theoretical considerations of the processes and mechanisms are given in Chapter I.2; the geological data are briefly reviewed below.

Gypsum is the most common primary marine sulphate and is the first to precipitate in evaporating basins. However, anhydrite can form as a primary deposit in evaporating basins when the temperature exceeds 25°C. Primary anhydrite is, however, rare and most anhydrite is believed to originate from dehydration of gypsum caused by the action of high pressure and temperature during burial. Other mechanisms and factors, which are discussed below, also affect these processes. Subsequent uplift of anhydrite formed during burial causes its re-hydration and conversion to

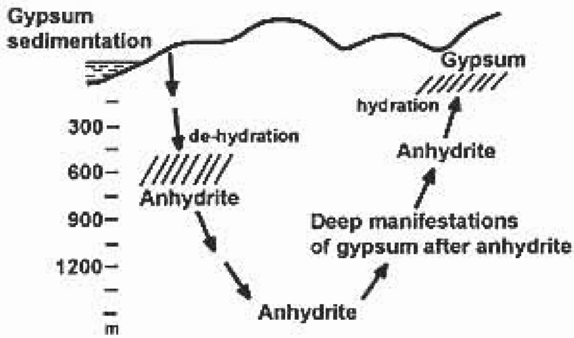

Fig.1. Dehydration-hydration cycle of sulphate rocks (after Murray, 1964).

secondary gypsum (Fig.1). The zonation of gypsum from anhydrite by the depth of occurrence is widely observed. The "gypsum-anhydrite divide" commonly exists at depths of 400-450 m in the subsidence phase of the cycle, and 150-100 m in the uplift phase. These figures can vary considerably from these generalities depending on the geothermal gradient, the supply of re-hydrating water and its chemical composition.

According to Strakhow (1962) the maximum depth of gypsum survival is around 450 m, a value also supported by the thermodynamic evaluations of Zverev (1967). However, gypsum is reported to occur on the depths up to 1200 m (Sonnenfeld, 1984) a figure more in keeping with the evaluations made by Mossop and Shearman (1973), and even below 3000 m (Ford & Williams, 1989). From the other hand, massive anhydrite occur in geological environments which have never experienced high lithostatic pressure or high temperatures such as the Messinian evaporites of the Mediterranean. Sonnenfeld (1984) provided experimental data suggesting that the factors of high pressure and temperature alone are not sufficient to explain the transition of gypsum to anhydrite. He has shown that the dehydration of gypsum occurs at shallow depths, mainly during the early stages diagenesis, due to its interaction with hygroscopic brines of Na, Mg or Ca chlorides. For dehydration during burial, many factors may determine the rate and effectiveness of the gypsum to anhydrite conversion; these include the tectonic regime, permeability and other properties of surrounding formations such as the flow regime. For instance, Jowett, Cathles-III & Davis (1993) suggested that gypsum converts to anhydrite at shallow depths (approx. 400 m) when it is overlain by poor thermal conductors such as shale or gypsum in a hot rift environment, and at great depths (hypothetically >4 km) when overlain by good thermal conductors like salt in a stable cratonic region.

It is widely believed that most gypsum has passed through the dehydration-hydration cycle. During the uplift phase, anhydrite frequently survives as masses at depths exceeding 100 m, though the main masses of anhydrite are generally found at depths below 450 m. In the upper zone of active groundwater circulation, sulphates are represented predominantly by gypsum. However, anhydrite is frequently dispersed, or preserved as local bodies within gypsum masses at quite shallow depths. Pechorkin (1986) showed that the "hydration front" is not clearly expressed and uniform, but has a complicated configuration that advances along many zones.

It may be concluded that, although some regularities in the geological occurrence of gypsum and anhydrite clearly exist, there are also many conflicts and deviations in the data. The situation is further complicated by the considerable age range of the formations, their complex geological histories and different tectonic regimes. The controversies in the interpretation of the geological data are supplemented by further theoretical difficulties in explaining gypsum-anhydrite-gypsum conversions; these are discussed in detail in Chapter I.2.

1.5. Fissures in gypsum rocks

It is universally accepted that fissures are of primary importance as pathways for the initial water circulation in most of karst rocks. This is even more true for gypsum and anhydrite because the effective porosity in these rocks is rather low and bedding partings are often not well preserved. The degree and structure of fissuring in gypsum and anhydrite vary greatly, from very low fissured beds to almost brecciated rocks. This depends on many factors including particularly the age of the rock sequence, its structure, tectonic setting, regime and the depth of occurrence.

Most karstologic works focus on tectonic fissuring as the control for karst development. These fissures commonly display sharp anisotropy and heterogeneity, forming hierarchies of structures. There are no clear peculiarities which can differentiate tectonic faults and fissures in gypsum from the similar structures in carbonates that are so well described in many texts.

The role of other genetic types of fissures is commonly overlooked. In gypsum, far more than in any other karstifiable rock, the role of endokinetic fissuring is very important for karstification. According to Tchernyshev (1983), endokinetic fissures are defined as those formed during petrogenetic processes from the energy provided by a very rock itself. In the Russian-language literature the term "lithogenetic fissures" is commonly used to indicate a wide class, contraction fissures being a characteristic sub-type formed by contraction of the sediment due to desiccation or cooling.

We believe that lithogenetic fissures can be formed in sulphate rocks throughout their history, not only during early diagenesis as it commonly implied. Other fracturing mechanisms are related to transformation processes including the loss of interstitial (pore) fluid by the solid rock, dehydration-hydration and recrystallization processes. However, the details are not well known and it is not quite clear exactly how contraction and fracturing can occur due to the loss of interstitial water in a rock that is already well lithified. It is a fact that these processes do occur well after the catagenesis stage, this is exemplified below.

There are some common characteristics which allow lithogenetic fissures and their networks to be distinguished from exokinetic fissures (tectonic and hypergene). Firstly, they are confined to certain layers and do not propagate into the adjoining beds. Secondly, they tend to form polygonal networks, which are more or less isotropic. Thirdly, the density of fissures in the networks is rather homogenous within a given site and the joint networks mainly (70-90%) form triple junctions (Tchernyshev, 1983).

Detailed spatial analysis by Klimchouk et al. (1995) proved that speleo-initiating fissures inherent to the structure of the huge maze caves in gypsum in the Western Ukraine (which have an

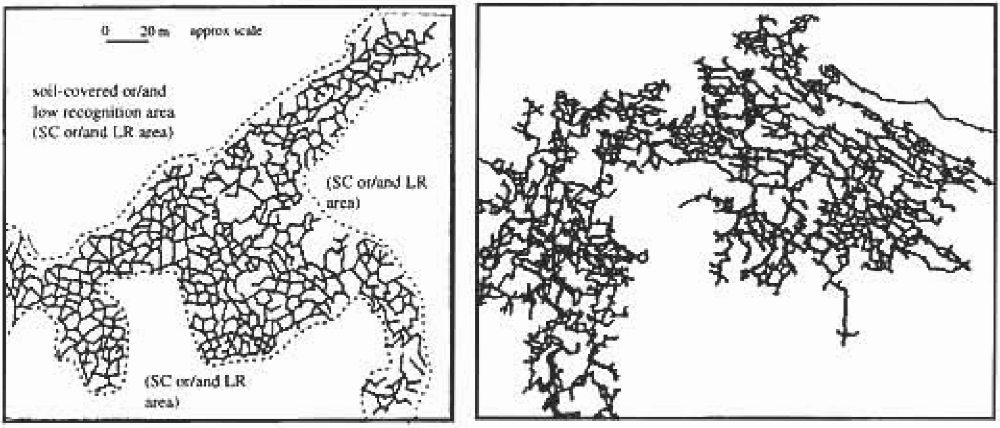

Fig.2. Patterns of lithogenetic fissures: left - on the exposed surface of the Permian gypsum in the North Texas, drawn by A.Klimchouk from the photo published in Miotke (1969); right - as revealed by a cave system developed in the Miocene gypsum in the Western Ukraine (the Nearest Series of the Optimisticheskaja Cave).

intrastratal setting), meet all the above characteristics and are of lithogenetic origin. However, they were formed well after the early diagenesis stage. This is evidenced by the fact that at least one generation of pre-speleogenetic fissures exist, which are sealed with marine sediments younger then the gypsum.

Exposed gypsum massifs in Sicily (Neogene gypsum) and in the North Texas (Permian gypsum) demonstrate similar fissure patterns (compare Fig. 2-A, 2-B and Plate 1). These are developed within the outer layer of the rock where the surface is concordant to the bedding. Such fissure networks were apparently formed after exposure of the gypsum. It can be deduced that the

Plate 1. Pattern of lithogenetic fissures on the exposed surface of the Messinian gypsum in Sicily (photo by U.Sauro).

contraction and tensile fracturing of the outer layer was caused by evaporative withdrawal of interstitial water from this layer.

In all the above cases, network patterns vary from pure polygonal (quasi-isotropic) to those where two or three sets are more clearly expressed. This is explained by the effect of a "mobile frame" (Tchernyshev, 1983; Klimchouk et al., 1995). They conclude that the stress field generated by contraction can be influenced by the external stress field caused by events (including tectonic events), transmitted from the surrounding (underlying and overlying) rocks; the result is that fracturing along certain directions is more pronounced.

It is remarkable that, despite the striking difference between settings, patterns of lithogenetic fissures display so much similarity. Similar patterns occur in the Western Ukraine, where the gypsum has never been exposed since it was covered by the Late Miocene marine deposits, and in Sicily and North Texas where differently aged gypsum was exposed to the surface during Pleistocene. This clearly illustrates the common nature of this phenomena, but it also suggests that the exposure of gypsum to the arid climatic conditions of Sicily and Texas is not a "must" for such fissures to form, although it have allowed some mechanism for the formation of lithogenetic fissures to operate in these cases.

1.6. Plasticity and flowage of sulphate rocks

One of the confusions about sulphate rock behaviour and gypsum karst development arises from the ambiguous interpretation of the deformation properties of these rocks. Gypsum is often viewed as a material capable, of some extent, to flow due to plasticity. It is therefore commonly believed that partings and fissures in the gypsum tend to close, thus preventing water circulation and karst development. Such a view, based largely on laboratory sample tests, is misleading. These tests show that, under certain conditions, gypsum and anhydrite display plastic, rather than brittle, deformation, the viscous creep component being much larger than elastic deformation. The behaviour of the sampled rock depends on many factors; these include the type, value and duration of a stress applied, the hydrostatic pressure, the amount and presence of a solution and it's chemical composition. However, the extrapolation of experimental data into the natural geological situation should be done with a great care. The above factors create extremely complicated fields in nature, each being superimposed upon another and changing with time; it is difficult to deduce their combined effects from the theoretical views or experimental data.

Geological evidence cited to support the flowage of gypsum rocks include swellings, waved structures, flow folding and similar features of the so called "gypsum tectonics" (Pechorkin, 1986); alternative explanations could also be considered for most of these cases. Pechorkin suggested that gypsum can flow from zones of high tectonic and gravitational stress to zones of lower stress forming flow structures as it moves. While such an effect appears doubtful in intrastratal conditions, it may perhaps account for the origin of some swelling structures at the surface of exposed homogenous gypsum massifs in situations where the stresses are released from one side. Such structures are best represented by the dome-like hills, that range in size from metres to tens of metres, and are often elongated along a certain direction; these are well expressed in the naked gypsum landscape of the gypsum massifs in Sicily (see Chapter I.8 in this volume). At the centre, or along the axis of such domes fissure-like openings can always be recognised. Their location displays a regular arrangement, perhaps related to the distribution of local tectonic stress and release zones; the latter are normally marked by the presence of a large fissure.

In contrast, numerous observations in caves occurring in an intrastratal setting prove that open fissures in gypsum layers can survive through geologically lengthy periods of time, suggesting that no rock flowage occurs (Klimchouk et al., 1995). From the authors' field experience it can be surmised that flow structures, due to plasticity, may form in gypsum only in the near-surface environment where the exposed gypsum rock mass is fairly homogenous and of considerable thickness. In intrastratal conditions a "frame effect" caused by the surrounding rocks and/or a strengthening effect caused by intercalated layers of other lithologies may prevent gypsum flow effects.

2. Lithological types of sulphate karst

Karst developed in gypsum, anhydrite and mixed sulphate rocks can be termed *sulphate karst*. Gypsum and anhydrite minerals may be present in varying proportions within a rock, but this is difficult to determine in the field. Sulphate rocks, down to depths up to 400-450 m (depending on the conditions of hydration) are represented mainly by gypsum. Karst development facilitates the hydration of anhydrite when it is present; furthermore, the dissolution of anhydrite is believed to proceed in conjunction with the hydration reaction (see Chapter I.2 in this volume). The above argument justifies the use of the term gypsum karst as a broad synonym for sulphate karst. There are no definite data about "pure" anhydrite karst, but it may possibly occur in deep-seated settings.

Gypsum and anhydrite are commonly associated with carbonates (dolomites and limestones), which are associated with the evaporitic suite of rocks. Carbonate rocks may underlie, overlie, or be intercalated with sulphate sequences. These may be referred to as sulphate-carbonate sequences, which are particularly common in the Palaeozoic evaporite formations. Adjacent or intercalated carbonates play a great role in gypsum karst development. They influence the initial permeability and flow paths in a sequence and affect the chemistry of karstification in the sulphates; they also help to control the geomechanical and geodynamic properties of sequence. Consequently, we suggest that the term *sulphate-carbonate karst* is used to distinguish and label karst systems in closely intercalated sequences.

Salts, natrium chloride in particular, are also commonly associated with gypsum and/or anhydrite. As the presence of other salts in solution enhances solubility of gypsum (up to 3 times) and dissolution rates, such lithological association is important for karstification in gypsum. For this reason the type of sulfate-salt karst is worst to be distinguished.

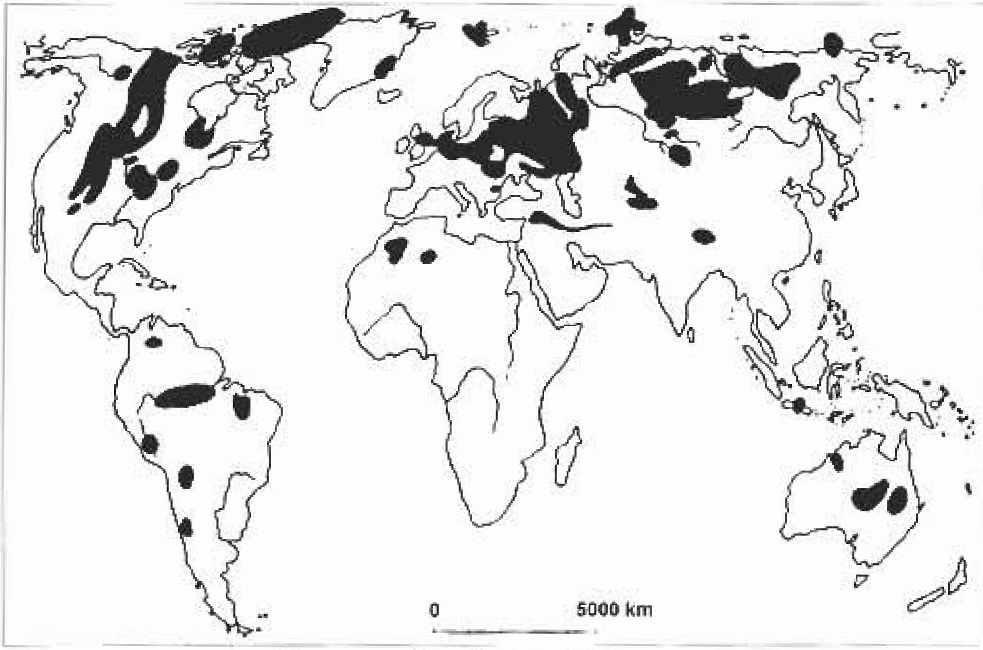

Fig.3. Areas of gypsum and anhydrite accumulation during the Pre-Cambrian and through the Palaeozoic.

3. Stratigraphical distribution of evaporate formations

The distribution of evaporate formations throughout the stratigraphical column displays some regularities which were outlined by Strakhov (1962):

1. Evaporite rocks began to appear at the end of the Proterozoic.

2. There are some epochs when almost no evaporite rocks were formed and other epochs when evaporite generation was extremely intense.

3. During halogenic epochs of the Palaeozoic a few very large evaporite deposits were formed. In contrast, through the Mesozoic to the Cenozoic the number of deposits formed was large, but they were of limited area and mass.

4. In general the halogenic epochs show some affinity to the epochs of orogenesis and regression, although the actual distribution is quite complex.

5. There is a regularity in the stratigraphic distribution of the different types of evaporite formations.

Continental formations represented by gypsum are know in the Carboniferous and the Neogene. Formations of lagoonal type can be traced from the Cambrian to the present, but formations in large gulfs are known mainly from the Cretaceous and Paleogene. Formations marginal to the vast epicontinental seas formed in the Devonian, and formations deposited in large internal salt-generating seas were common in the Permian.

The most extensive and thick sulphate formations have formed during the Palaeozoic. Fig.3 (drawn from data presented by Zharkov, 1974) shows superimposed areas of gypsum and anhydrite accumulation around the globe for different epochs from the pre-Cambrian through to the Permian. During the Mesozoic and Cenozoic, sulphate rocks have formed in numerous relatively small basins which surrounded young tectonically active areas, particularly the Paratethis (Alps, Carpathians, Caucasus, mountains of Central and Southern Asia). Gypsum and anhydrite are widespread throughout the Cenozoic, they are particularly developed in the Miocene formations of the Mediterranean region (in the Pyrenees and Appennines, Sicily and North Africa), along both sides of the Carpathian mountain arch. Neogene gypsum is know in the epiplatform environment of the Ustjurt Plateau and mountainous regions of Central Asia (Pamir-Alaj, Bajsuntau, Kugitangtau), as well as in some regions of Turkey.

4. Global distribution of gypsum and anhydrite

Ford & Williams (1989) estimated that sulphate rocks and/or salts underlie 25% of the continental surface of the world, an area of more than 60 million km^2. Maximovich (1964) calculated that the area of gypsum/anhydrite present on the continents was 7 million km^2. Both sets of figures are quite approximate. The largest areas of sulphate rocks are located in the Northern hemisphere, particularly in the United States where they underlie about 35-40% of the nation's land area (Johnson, 1997, this volume) and Russia where Gorbunova (1977) estimated a figure of 5 million km^2 for the former USSR. Sulphate rock outcrops are generally much smaller than those of the carbonates. However, gypsum karst develops widely in intrastratal conditions, and this type of karst is similar in extent to the carbonate intrastratal karst (see I.4 in this volume). The geographic distribution of gypsum karst is further discussed in the Part II of this book; Chapter II.1 presents a brief overview, and the succeeding papers describe gypsum karst in individual countries where it is widely developed.

5. Tectonic and structural settings of gypsum karst

Evaporate formations containing gypsum and anhydrite occur in various modern tectonic settings including: platform depressions of various kinds, foredeeps, orogenic regions, intermountain troughs, rift depressions and intercontinental post-orogenic depressions. In the context of karst, we are most concerned with continental tectonic settings. In general, it is possible to distinguish between gypsum karst development in platform regions, foredeeps and orogenic regions; each of these settings imposes specific structural features on the sulphate sequence which determine important peculiarities of gypsum karst development.

Platform regions often geomorphologically correspond to planes where the sulphate rocks have horizontal to gentle dips (1-5°) and crop out over large areas ranging up to tens of thousands of km^2. A block-fault structure is common, sometimes with a system of faults and blocks that have little vertical displacement between them. Fissuring in gypsum is common and of relatively shallow occurrence; it is often rather uniformly distributed and the fissures may be of tectonic, lithogenetic or mixed origin (see above). Intrastratal karst is by far the most dominant type in this setting (for the typology of karst according to it's coverbeds and evolution see Chapter I.4). It develops at varying depths beneath the cover. The development of karst and it's expression at the surface depends mainly on the depth of occurrence of sulphate rocks and the geomorphic evolution of the terrain. Large valleys incised through the coverbeds greatly influence the hydrogeological flow architecture both on a local and a regional scale; consequently, karst development occurs at considerable depths beneath the valley bottoms. When karst has evolved, gypsum sequences often behave as good aquifers. However, the most pronounced hydrogeological role of gypsum karst, in the platform setting, is the fact that it governs the cross-formation communication between major aquifers adjacent to the gypsum (Chapter I.6). The stable platform tectonic regime and the rather slow groundwater circulation, favour intrastratal karst development. This occurs over quite prolonged time spans and is intensified when gypsum formations are brought into a shallower position by active uplift. Karst landscape evolves as gypsum is exposed by entrenched fluvial erosion or by denudation and scouring. Examples of gypsum karst in platform settings are numerous and occur throughout North America, Europe, Siberia and China (see Chapters II.2, II.3, II.5, II.8, II.12, II.13).

In foredeeps the strata are usually gently folded with a dips of up to 10-15°. The rocks are often displaced and broken by faults so that their lateral continuity is disrupted. Areas of outcrop and near-surface gypsum are linear, elongated along the strike of the foredeep or local fold structures. Sulphates tend to plunge down-dip to considerable depths below non-karstifiable sequences. The karst that develops is limited in area, but is often quite intensive. Situations where aquifers are confined beneath low-permeable cover favour the localised upward recharge through the gypsum strata especially where it is focused along tectonic faults resulting in the intense karstification of such zones. Large and deep collapse features are common in this structural setting. An outstanding example of gypsum karst in a foredeep setting is the sulphate belt of the Ural foredeep (see Chapter II.11). Similar tectonic settings can occur at the edges of concealed platforms where they pass into the adjacent foredeeps, such as the situation in the Western Ukraine (see Chapter II.9).

In orogenic regions, sulphate rocks are commonly severely folded with considerable varying dips reaching vertical and even overturned. The areas where gypsum underlies the surface at shallow depths are commonly rather small, but often well exposed with outcrops larger than those seen in platform or foredeep settings. The rocks are densely fissured sometimes resulting in a breccia; the fissure systems may be of various ages and genesis superposed on each other. However, re-crystallisation and other processes which occur in exposed gypsum masses, often result in sealing of fissures, at least in the outer zone (see above, and in Chapter I.9). The features of exposed karst in orogenic regions are different. Some massifs exhibit an extremely high density of surface karstification expressed as honeycomb or badland-like landscapes (North Caucasus, Central Asia); others display relatively scarce point-recharge forms such as dolines and blind valleys with the development of some kind of outer crust on the gypsum which prevents dispersed recharge and karstification (Apennines, Sicily, South of Spain; see Chapter I.9). Underground drainage systems (caves) in all cases appear to be formed by the adjustment of the contemporaneous geomorphic systems; they tend to be linear, directly connecting recharge and discharge points. The above differences probably depend on the paleogeography, the previous (pre-exposure) karstification history of the formation and the regional tectonic regime. Data about deep-seated karst in this orogenic setting are not known to the authors.

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