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GYPSUM KARST OF THE WORLD

Edited by
Alexander Klimchouk, David Lowe, Anthony Cooper & Ugo Sauro

Issued on the occassion of:

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PART II: Regional reviews and case studies

Preface

Karst associated with gypsum and anhydrite rocks, referred to throughout this volume as gypsum karst, has received relatively little appreciation in the mainstream of international karstology, and has commonly been considered a rather enigmatic topic. On the one hand, some tremendous maze caves are known within gypsum deposits, including the second longest cave in the world and some other truly vast systems. In general, dissolutional phenomena in gypsum, and the hazards associated with them, are of widespread interest and concern to environmentalists and engineering geologists throughout the world. On the other hand, there is a wide-ranging belief among karstologists that gypsum karst develops only in relatively restricted areas, and that sulphate rock properties, such as dehydration-hydration conversions, or rock flowage and permeability sealing, prevent the "full" development of karst systems. Moreover, gypsum karst is commonly regarded as something that is somehow related to the original karst concept, but not true karst in its own right. However, at least some aspects within these views are misleading, as is argued convincingly and illustrated clearly by the contents of this volume.

Although, on the global scale, surface gypsum outcrops appear relatively limited, these rocks occur widely within the upper few hundred metres of many rock sequences, below various types of cover beds, and karst processes operate extensively in such settings. Partly because of this situation, and because of peculiar dissolution processes of gypsum, the environmental hazards induced by gypsum karst are potentially even more severe than those associated with carbonate karsts. In this book an attempt is made to investigate gypsum karst in the full variety of its occurrences, in appropriate relation to their regional significance, not just to consider exposed settings.

A major goal of this volume is to present a representative picture of gypsum karst around the world, demonstrating the wide diversity of its types and of its morphology, hydrology and hydrogeology. This is achieved partly by means of a series of review papers, written by leading experts from many countries, that characterize the features of the most important gypsum karst regions. These selected reviews do not provide an exhaustive account of all the world's gypsum karsts but, hopefully, they succeed adequately in conveying the regional diversity that justifies the title of the volume.

Another major role of the book is to provide overviews and summaries of the present level of knowledge about gypsum karst, and the conditions of its development. The aim is to categorize the processes, mechanisms and characteristics that are either common with, or distinct from, those associated with the more familiar carbonate karsts. Several challenges have had to be faced in attempting this.

One challenge was that the conceptual framework of traditional karstology is based largely upon a "geomorphological" paradigm and is thus not ideally suited to encompassing the deep-seated karst phenomena that are commonly, but often misguidedly, viewed as palaeokarst. It seemed necessary to re-state and modify some basic concepts and definitions, to allow a more organic incorporation of both aspects (deep-seated phenomena in general and gypsum karst in particular) into the overall conceptual structure of karstology and speleology. The task extends far beyond the scope of the volume, and is definitely far from being completed, but at least some initial steps have been taken towards its eventual achievement.

Another problem was that many of the ideas developed, and knowledge gained, about gypsum karst, comes from the former Soviet Union, which encompasses the world's most extensive gypsum karst regions. More than half of all the works published on the subject were written in Russian. The basic concepts and terminology discussed in Russian-language literature differ in many aspects from those developed by

Western karstologists, so that it has not been possible simply to compare, or mechanically combine, ideas and data directly. The challenge was to choose and/or develop a conceptual framework within which to identify and integrate the best approaches and findings of the different karst research schools.

The most important work on gypsum karst in the former Soviet Union was carried out by G.Maximovich, K.Gorbunova, V.Lukin, A.Iljin, I.Pechorkin, A.Pechorkin, V.Dubljansky, V.Andrejchuk and A.Klimchouk. Among the many speleological groups that have explored gypsum caves in different areas, special credit is deserved by speleologists from Ternopol, L'vov, Chernovtsy and Kiev in the Ukraine, whose efforts and dedication since the early nineteen-sixties resulted in the exploration and survey of some 450km of cave passages in the largest gypsum caves in the world.

In other countries, important and detailed studies of gypsum karst and caves have been performed in Italy (by O.Marinelly, P.Forti, U.Sauro, T.Macaluso, V.Agnesi, P.LaManna, and the speleological groups of Emilia-Romagna and Sicily), in Germany (by K.Gripp, A.Hermann, S.Kempe, D.Miotke, F.Reinboth, K.Priesnitz, M.Kupetz, M.Brust, R. & C.Volker and others), in France (by J.Nicod and M.Chardon), in Great Britain (by A.Cooper and others), in Spain (by J.M.Calaforra, A.Pulido-Bosch, F.Gutierrez, and the speleological group of Almeria) and in the United States (by J.Quinlan, K.Johnson, the GYPKAP Project).

Several published works have provided overviews of the large-scale regional aspects of gypsum karst studies (Gorbunova, 1977 for the USSR; Quinlan; 1978 and Quinlan et al, 1986 for the USA; Nicod, 1993 for the world). K.Gorbunova (1979) published an important book reviewing morphology and hydrogeology of gypsum karst, and A.Pechorkin (1986) summarized the geodynamics of gypsum karst. However, there are several reasons why a new attempt to produce a fundamental review on the topic was worth the necessary effort: 1) rapid development of new ideas in karstological and speleogenetic studies during the last two decades has given important and powerful new insights that are applicable to the interpretation of karst phenomena in gypsum, 2) several detailed studies have recently been undertaken in gypsum karst areas in different countries and, 3) the pre-existing Soviet and Western reviews were all lacking in adequate coverage of ideas and regional data from "the other side".

The idea to produce this volume was born some years ago among an international group of karst and cave scientists who were working on gypsum karst: Professor P.Forti, Dr J.M.Calaforra, Dr V.Andrejchuk and myself. Even though some of the original collaborators were unable to participate more extensively in the final preparation of this volume, due to their recent individual circumstances, the mutual inspiration provided by the above team has been decisive to the eventual realization of the volume.

Production of the volume "Gypsum Karst of the World" was coordinated by myself, as I was able to focus time and effort on the task thanks to a scholarship that was provided by the University of Padova, Italy. My co-editors, Dr D.J.Lowe, Dr A.Cooper and Professor U.Sauro have provided extremely valuable cooperation, both in terms of their organizational efforts and their careful scientific and linguistic editing of the contents of the volume.

The editors and contributors hope that this publication will give some important insights to the proper recognition and understanding of gypsum karst phenomena and processes, encourage further studies of the topic and facilitate solutions of the relevant practical problems.

Alexander Klimchouk

PART I

GENERAL AND SPECIAL TOPICS

Chapter I.1

SULPHATE ROCKS AS AN ARENA FOR KARST DEVELOPMENT

Alexander Klimchouk & Vjacheslav Andrejchuk

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)

<table>
<tr><th>Sub-class</th><th colspan="2">Mineral</th><th>Formula</th></tr>
<tr><td rowspan="6">Na - sulphates</td><td colspan="2">Tenardite</td><td>Na_2SO_4</td></tr>
<tr><td colspan="2">Mirabilite</td><td>$Na_2SO_4 x 10H_2O$</td></tr>
<tr><td colspan="2">Glauberite</td><td>$Na_2SO_4 x CaSO_4$</td></tr>
<tr><td colspan="2">Vantgoffite</td><td>$3Na_2SO_4 x MgSO_4$</td></tr>
<tr><td colspan="2">Leoveite</td><td>$Na_2SO_4 x MgSO_4 x 2H_2O$</td></tr>
<tr><td colspan="2">Astrakhanite</td><td>$Na_2SO_4 x MgSO_4 x 4H_2O$</td></tr>
<tr><td rowspan="6">K - sulphates</td><td rowspan="5">K_1 - sulphates</td><td>Glaserite</td><td>$(K_1Na)_2SO_4$</td></tr>
<tr><td>Gergeite</td><td>$K_2SO_4 x 5CaSO_4$</td></tr>
<tr><td>Langbeinite</td><td>$K_2SO_4 x 2MgSO_4$</td></tr>
<tr><td>Shenite</td><td>$K_2SO_4 x MgSO_4 x 7H_2O$</td></tr>
<tr><td>Polygalite</td><td>$K_2SO_4 x MgSO_4 x 7CaSO_4 x 2H_2O$</td></tr>
<tr><td>K_2 -sulphates</td><td>Kainite</td><td>$KCl x MgSO_4 x 3H_2O$</td></tr>
<tr><td rowspan="2">Ca - sulphates</td><td colspan="2">Anhydrite</td><td>$CaSO_4$</td></tr>
<tr><td colspan="2">Gypsum</td><td>$CaSO_4 x 2H_2O$</td></tr>
<tr><td rowspan="2">Mg -sulphates</td><td colspan="2">Kiserite</td><td>$MgSO_4 x H_2O$</td></tr>
<tr><td colspan="2">Epsomite</td><td>$MgSO_4 x 7H_2O$</td></tr>
</table>

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

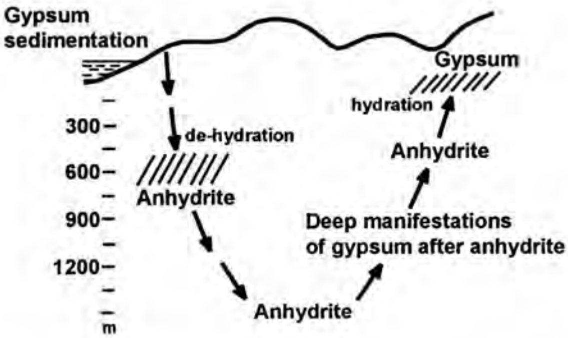

Fig.1. Dehydration-hydration cycle of sulphate rocks (after Murray, 1964).

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 Strakhov (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

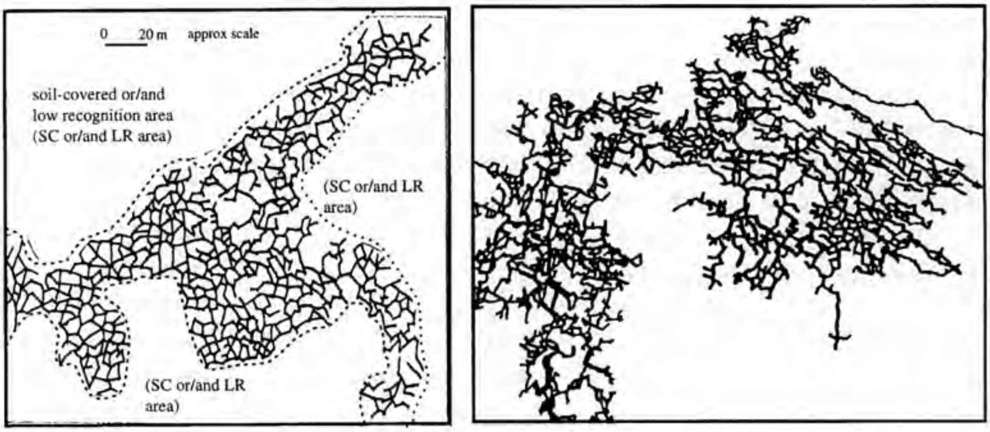

Fig.2. Patterns of lithogenetic fissures: left - on the exposed surface of the Permian gypsum in the North Texas, drawn by A.Klimchouk from the photo published in Miotke (1969); right - as revealed by a cave system developed in the Miocene gypsum in the Western Ukraine (the Nearest Series of the Optimisticheskaja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

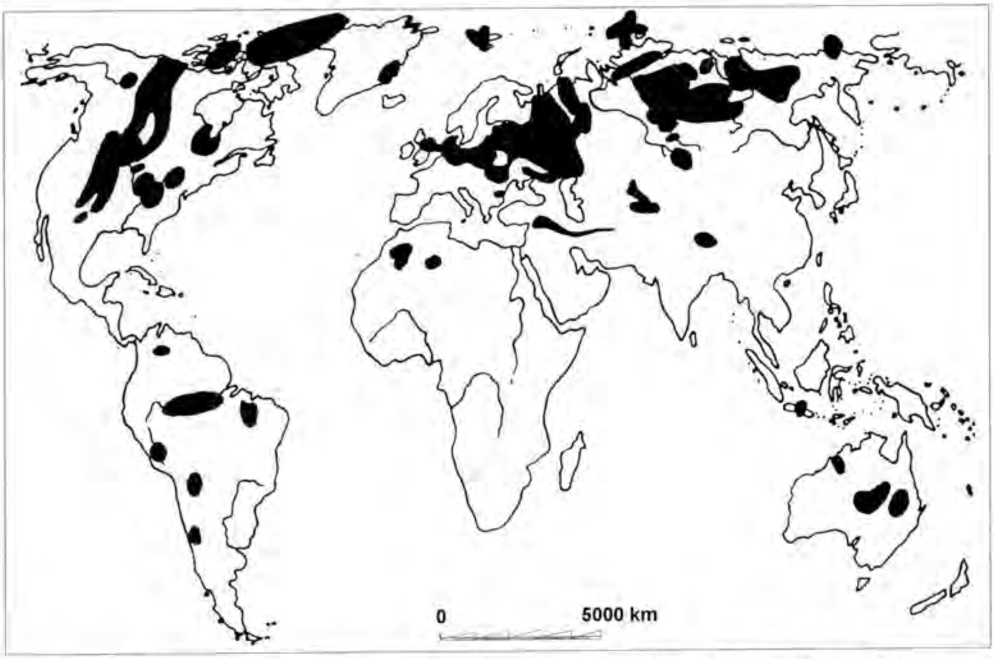

Fig.3. Areas of gypsum and anhydrite accumulation during the Pre-Cambrian and through the Palaeozoic.

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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Chapter I.2

THE DISSOLUTION AND CONVERSION OF GYPSUM AND ANHYDRITE

Alexander Klimchouk

The development of karst is a complex system driven by the dissolution of a host rock and the subsequent removal of dissolved matter by moving water. It is the process that, at various stages, initiates or triggers associated processes including erosion, collapse and subsidence. The dissolution of sulphate rocks proceeds by different mechanisms and at different rates to those associated with the dissolution of carbonate rocks. For each rock type different factors influence the process. This chapter is an attempt to summarise the present knowledge of the dissolution chemistry and kinetics of gypsum and anhydrite. These are important for the genetic interpretation of karst features in these rocks. The gypsum-anhydrite-gypsum transitions and recrystallization processes are also addressed, because of their importance to karst development.

Many studies have been undertaken on the solubility and dissolution of sulphate minerals, in the context of construction engineering and karst processes. Important works include these of Laptev (1939), Kuznetzov (1947), Shternina (1949), Zdanovsky (1956), Sokolov (1962), Zverev (1967), Lui & Nancollas (1971), Blount & Dickson (1973), Mel'nikova & Moshkina (1973), Wigley (1973), Gorbunova (1977), James & Lupton (1978), Kushnir (1988). The most comprehensive recent account is that of James (1992).

1. Chemical equilibria

Gypsum dissolves by a simple two phase dissociation (solid and solvent):

$$CaSO_4\ 2H_2O == Ca^{2+} + SO_4^{2-} + 2H_2 \qquad [1]$$

Gypsum, like $CaCO_3$ and salt, dissolves reversibly, but anhydrite does not. When anhydrite is dissolved it forms a solution of calcium sulphate which, at common temperatures and pressures, is in equilibrium with the solid phase of gypsum, but not with anhydrite. If disequilibrium of the solid-solvent system occurs, gypsum precipitates. This is due to the instability of anhydrite under normal surface and shallow sub-surface thermobaric conditions (Fig.1).

The solubility of gypsum in pure water at 20°C is 2.531 g/L, or 14.7 mM/L. It is roughly 140 times lower than the solubility of common salt (360 g/L) but four orders of magnitude greater than the solubility of $CaCO_3$ (1.5 mg/L); however, in the presence of CO_2 the dissolution of calcite is enhanced and the difference in solubility between calcite and gypsum decreases to 10-30 times.

The dependence of the solubility of gypsum on temperature is reported by many authors (Blount & Dickson, 1973; James, 1992; Liley et al, 1963; see Fig.2). Between 0 and 30°C, the range encompassing most natural waters, the solubility of gypsum increases by 20%, reaching a maxi-

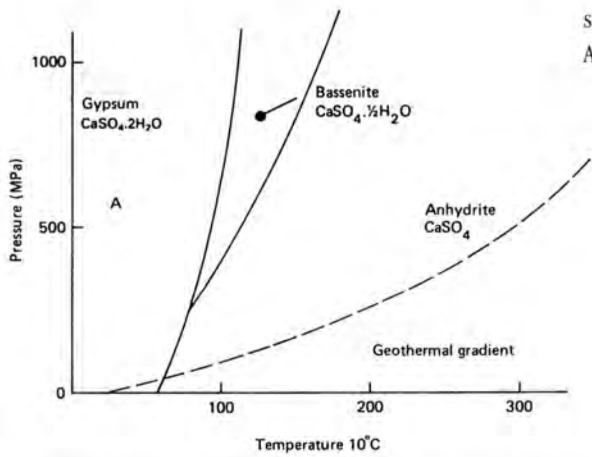


Fig.1. - Equilibrium diagram for the system $CaSO_4$ - H_2O (after Zanbak & Arthur, 1986).

mum (about 2.66 g/L) at 43°C. Cigna (1985) examined the possible effects on gypsum solubility caused by mixing waters at different temperatures. He found that when mixing equal amounts of two saturated waters (one at 10°C, and another at temperatures ranging from 40 to 100°C) the solubility in the mixture increased by between 2 and 13%. This effect may play some role in the karstification of areas with geothermal waters.

Anhydrite may be considered to have no characteristic solubility. This is because of its chemical instability in commonly encountered shallow sub-surface conditions (James, 1992). Some values given in the literature are misleading: the true solubility of anhydrite under normal temperatures is equivalent to that of gypsum. When dissolved in water, anhydrite produces a solution of $CaSO_4$ that ultimately attains the same equilibrium concentrations as the gypsum-H_2O system in pure water, this is 2.00 g/L at 20°C. James (1992) pointed out that anhydrite in contact with water

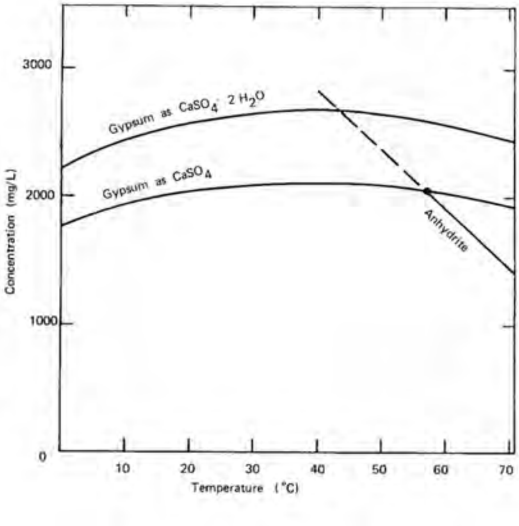


Fig. 2. Solubility curves for gypsum and anhydrite based on the experimental data of Blount & Dickson (1973). The upper curve pertains to the mass loss of gypsum rock in solution. The lower curve is calculated as $CaSO_4$ and displays the invariant point at 58°C, where gypsum, anhydrite and liquid coexist (After White, 1988).

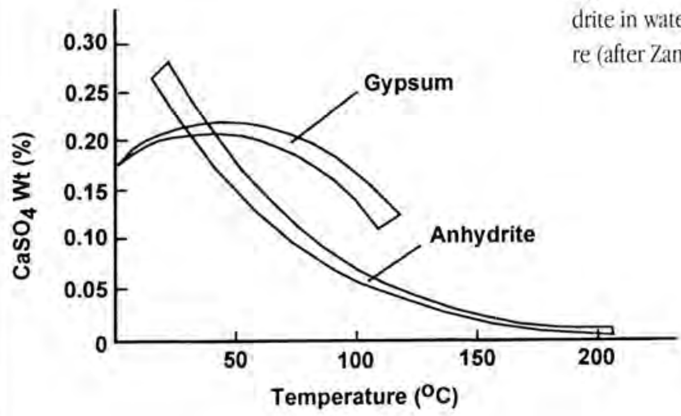


Fig. 3. - Solubility of gypsum and anhydrite in water at one atmosphere pressure (after Zanbak & Arthur, 1986).

tends towards a metastable state characterised by supersaturated solutions. These probably account for some of the high solubilities quoted for anhydrite, which range up to 3.5 g/L. The subject of gypsum/anhydrite conversion is described in detail in section 5 below.

Figure 3 shows the solubility data for anhydrite and gypsum in their stability regions; this information was summarised by Zanbrak & Arthur (1986). The solubility of anhydrite is lower than that of gypsum under these pressure conditions, and decreases with increasing temperature.

Pressure does not substantially affect the solubility of gypsum within common geological environments. In contrast the $CaCO_3$-CO_2-H_2O system is influenced by the presence of a gas phase that makes it sensitive to pressure. The solubility of gypsum increases slightly at pressures exceeding 100 bars (Manikhin, 1966), but at depths of less than a thousand metres or so, the influence is negligible. The effect of pressure applied to the mineral is discussed below.

Equilibrium constants. Different equilibrium constant values for gypsum Kg are reported by various authors, reflecting varying experimental conditions and the use of different thermodynamic data in the calculations. The constants are most usually given for 25°C and higher temperatures. However, in many karst environments the water temperature range is more normally between 5 and 15°C. Aksem & Klimchouk (1991) provided thermodynamic calculations of Gubbs free energy values and equilibrium constants for the gypsum dissolution reaction in water at temperatures of 0-50°C (Table 1). The results agree closely with the values previously provided by Wigley (1973). The data in Table 1 give the following Kg function of temperature:

$$pKg = 4.667 - 5.197 \times 10^{-9} \times t + 1.133 \times 10^{-4} \times t \qquad [2]$$

Saturation index. Karst waters in equilibrium with a solid phase are rare. When a solution is undersaturated with respect to the soluble mineral, dissolution proceeds; no dissolution occurs, or there may be precipitation, when the solution is supersaturated. Precipitation does not always occur in supersaturated solutions, its triggeringand progress depend on many causative factors.

The deviation of a solution from equilibrium is measured by the saturation index SI, introduced by Langmuir (1971) and used widely by karst researchers (see White, 1988; Ford and Williams, 1989, for a description of the general concept). The saturation index is defined as the relation of the ion activity product for the dissociation of the mineral to the thermodynamic equilibrium constant K of the reaction. For gypsum the saturation index is:

$$SIgyp = \log a\,(Ca^{2+})\;\; a\,(SO_4^{\;2-})\,\gamma Ca\;\, \gamma SO_4 / Kg \qquad [3]$$

where: γCa and γSO_4 are coefficients accounting for the ion pairing effect.

SI is zero if water is in equilibrium with the mineral, it has negative values for undersaturated (aggressive) solutions, and positive values for supersaturated solutions.

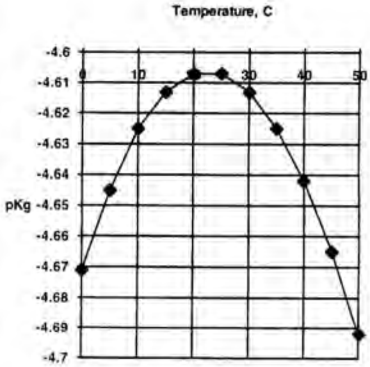


Fig. 4. Equilibrium constant Kg as a function of temperature.

In natural conditions equilibrium is rarely attained, or it is disrupted by changes in factors and conditions that affect solubility. The dependence of the solubility on various properties of a solvent and solid are not clearly and unambiguously described either theoretically or by quantifiable means. The main factors affecting the *solubility of gypsum* are oulined below.

2. Main factors affecting the solubility of gypsum

Pressure applied to the rock. Korzhinsky (1953) showed that the solubility of minerals increases when the rock fabric experiences pressures higher than that of the groundwater. Experimental data by Manikhin (1966) suggest that the solubility of anhydrite increases sharply with the increase in pressure: each 0.01 Pa increase in pressure results in a 3 to 5 times increase in the solubility. The solubility of gypsum is reported to increase 4 times with each additional 0.1 Pa. Consequently, the solubility of anhydrite becomes higher than that of gypsum under applied stress. Pecherkin (1986) discussed the stress field in the Polazna gypsum/anhydrite massif of the Urals and, referring to Manikhin's data, evaluated that the solubility of anhydrite in the zones of high stress should be 2 to 5 times higher than in the low stress areas. This factor is believed to have a significant role in the differentiation of dissolution-recrystallization and hydration processes on a massif scale. For gypsum, the increase in solubility with depth caused by the above effect will be about 6% at a depth of 50m (average pressure 1.5×10^{-4} Pa) and about 14% at a depth of 100 m (2.3 x 10-4 PA). The effect is likely to be important to karst development in all

T °C	GT, kal	pKg	Kg x 10^5
0	5839	4.671	2.131
5	5912	4.645	2.266
10	5993	4.625	2.370
15	6082	4.613	2.439
20	6183	4.607	2.472
25	6286	4.607	2.471
30	6400	4.613	2.436
35	6522	4.625	2.370
40	6653	4.642	2.278
45	6791	4.665	2.165
50	6938	4.692	2.034

environments, not just in deep-seated ones.

Grain size. G.Hewlett reported that saturation with respect to gypsum for grains of 2m in size is reached at a concentration of 15.3 mM/L. However, for 0.3m-sized grains the solution becomes saturated at 18.2 mM/L and the solubility effectively increases by 20% (cited after Sokolov, 1962). Sonnenfeld (1984) indicated that the solubility of gypsum reaches a maximum for crystals in the size range of 0.2 - 0.5μ, whereas the solubility of anhydrite is highest for crystals around 2.8μ in size.=

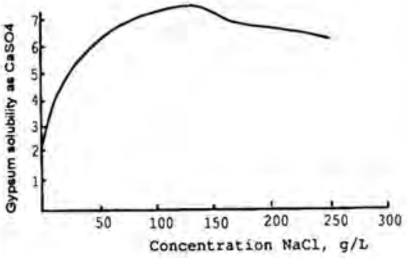
Differential solubility with respect to grains of different sizes results in interstitial (pore) waters that can be undersaturated with respect to small-sized grains, but supersaturated with respect to large grains. This plays an important role in recrystallization and hydration processes (see sections 5 and 6 below), and perhaps in the development of irregular small-scale porosity. Selective dissolution within heteroblastic rock may facilitate surface retreat by water because of the preferential removal of small-sized grains that initially provide a cement between the larger ones. The differential solubility of crystals of various sizes is illustrated well by observations made in the gypsum caves of the Western Ukraine, where single giant crystals of selenite within the heteroblastic rock mass commonly protrude from the walls and ceilings as pendants. They are apparently less soluble than the surrounding, finer-grained, matrix.

Solubility in various salt solutions. All natural waters contain some dissolved salts, and it is well known that these can affect the solubility of other minerals.

Ion pairing effects reduce the activity of ions and result in increased solubility. Ford & Williams (1989) noted that an increase of up to 10% in gypsum solubility was possible in typical karst waters. However, they stressed the far greater importance of the effect on the values of calculated saturation indexes. If pairing is not taken into account, the SI values are overestimated. It is likely that many reported cases of supersaturated waters in gypsum karst are actually related to this effect.

The presence of ions foreign to the solid phase considerably increases the solubility of gypsum due to the enhanced ionic strength of the solution; figure 5 shows the effect of NaCl (after Shternina, 1949). With increasing concentrations of sodium chloride the solubility of gypsum increases. After quickly reaching a maximum of 7,326 mg/L at 138.75 g/L of NaCl, it then decreases slowly, but remains much higher than the solubility in pure water. The solubility of gypsum in solutions containing other salts is higher still; the presence of $Mg(NO_3)^2$ can boost the solubility of gypsum by almost 6 times when compared with the value for pure water. Figure 6 is taken from the work of Shternina (1949) and shows similar curve shapes, although characteristic points are different. The study of complex systems, common in nature (Mel'nikova & Moshkina, 1973) indicates gypsum solubilities of 5.9 to 6.3 g/L in solutions containing high concentrations of $MgSO_4$ (5.6 to 18.2%) and NaCl (0.2 to 14.1%). James (1992), referring to Paine et al, (1982), quoted a good example from the Poechos dam in Peru. Here direct determinations of the solubility of gypsum in groundwater samples from wells, gave $CaSO_4$ values as high as 6.2 g/L , three times the solubility in pure water and 35% more than the maximum solubility in sea water; these water samples also contained Na, K, Mg, HCO_3, Cl, SO_4 and NO_3 ions.

The effect of foreign ions is very important for gypsum karst development. Other salts are



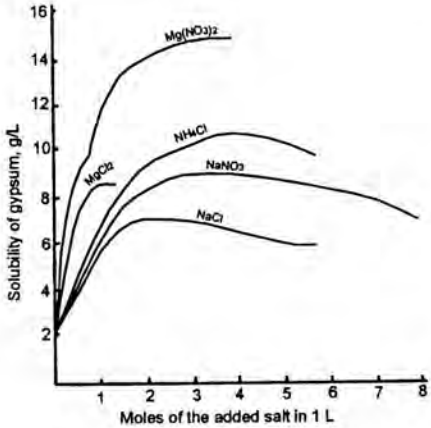


Fig.5. The dependence of solubility of $CaSO_4$ on concentrations of NaCl in solution at 25°C (After Shternina, 1949).

Fig.6. The solubility of gypsum in water solutions of salts at 25oC (After Shternina, 1949).

commonly associated with gypsum in evaporate formations and the groundwater of many aquifers, particularly the deep-seated ones, may contain high levels of dissolved salts.

The presence of common ions in solution (ones which are the same as the dissolving mineral, but introduced from some other source), decreases the solubility of the common mineral. Ca^{2+} is the common ion for gypsum and calcite and the effect occurs in many karst areas where intercalated or adjacent sulphate and carbonate layers occur. The effect is more pronounced with respect to the solubility of calcite and is of lower significance for gypsum dissolution. The study of the system Ca^{2+} -HCO_3^- - SO_4^{2-} - H_2O by Wigley (1973) allows the assessment of the relative contributions to the total concentration of calcium of calcium derived respectively from gypsum and calcite. It also allows the evaluation of the equilibrium (disequilibrium) for each mineral (Fig.7). The partial pressure of CO_2 is an independent variable influencing the solubility of calcite, but it has a negligible effect on gypsum solubility (Sokolov, 1962). Zdanovsky (1956) suggested that the solubility of some salts, including gypsum, decreases slightly with increasing CO_2. Where only gypsum dissolves, but CO_2 is supplied to the water from soil cover or from other sources, net deposition of calcite may occur as saturation with respect to $CaCO_3$ is quickly reached. The relationship between gypsum dissolution and calcite deposition in the presence of CO_2, in the shallow subsurface, was studied by Forti & Rabbi (1981). They calculated the equilibrium pattern for the CO_2 - H_2O - calcite - gypsum system with respect to CO_2 and pH (Fig.8). The effect is responsible for calcite deposition in many gypsum caves that are close to the surface, but it is also responsible for the replacement of gypsum with calcite in the reducing environment of some confined aquifers. However, since the effect has a low influence on gypsum solubility, and since much gypsum disso-

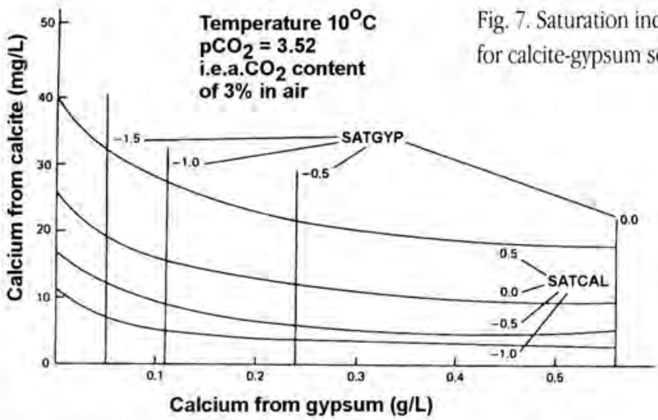


Fig. 7. Saturation index curves for calcite-gypsum solutions (After Wigley, 1973).

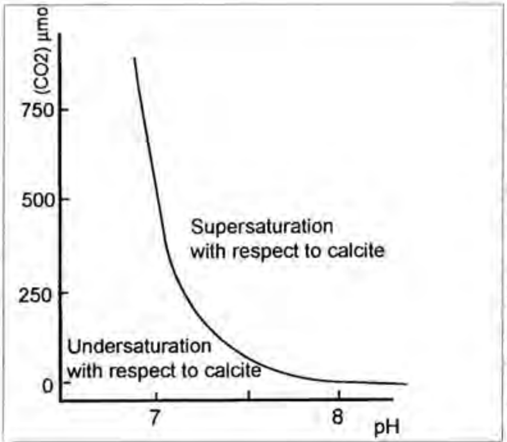
lution occurs without any CO_2 involvement, it appears unreasonable to claim gypsum karst as a three-component system (Forti & Rabbi, 1981).

3. Factors maintaining the dissolution potential with respect to sulphates

Sulphate reduction. The reduction of dissolved sulphates by microbes (including heterogeneous assemblages of Desulfo-x) is a common process in confined aquifer systems where sulphate rocks and dispersed organic matter are present. The process is described by the following simplified reaction:

$$SO_4^{2-} + 2CH_2O \xrightarrow[\text{anaerobic bacteria}]{} H_2S + 2HCO_3^- \quad [4]$$

Fig. 8. The equilibrium pattern for the system CO_2 - H_2O - calcite - gypsum with respect to CO_2 and pH at 10°C (After Forti & Rabbi, 1981).



During sulphate reduction, sulphate ions are consumed and removed from the solution, making it able to dissolve more sulphates. Calcium and bicarbonate commonly react to precipitate $CaCO_3$, utilising the HCO_3^- generated by the above reaction. Epigenetic calcite masses can also form as a result. Calcium cations can also be exchanged with sodium derived from intercalated or surrounding rocks. Sulphate reduction appears to be a very important mechanism in maintaining the dissolution potential of groundwater with respect to gypsum in confined aquifers, especially if vertical cross-formational hydraulic communication is present (see Klimchouk, 1997, Chapter I.5 in this volume). In hydrochemistry the effect has been known for a long time and its possible general relevance to karst development had been outlined by Kaveev (1963), Turyshev (1965) and some other workers. Recently its actual importance for speleogenesis in gypsum has been emphasised by Klimchouk (1994; 1996).

De-dolomitization. Dolomite is commonly associated with or intercalated with gypsum. Stankevich (1970) pointed out that the process of de-dolomitisation generates further dissolutional capacity with respect to gypsum, because Ca^{2+} is removed from solution and the sulphate ions react with the Mg. The process favours the development of gypsum karst in deep-seated environments.

Suspended crystals. Pechorkin (1986) reported experimental results suggesting that when a solution approaches gypsum saturation, small crystals originate in the presence of the solid phase. These can then be carried in suspension by flowing water. Such crystals begin to form at $CaSO_4$ concentrations of 1.1 to 1.5 g/L and reach a maximum of 10-15% of the total dissolved $CaSO_4$ at concentrations of 2.2 g/L. Thus, an additional 0.28 - 0.42 grams of gypsum can be dissolved in each litre of water. The cited author did not discuss what causes precipitation in undersaturated solvents.

4. The dissolution kinetics of gypsum and anhydrite

Dissolution is a heterogeneous reaction occurring at the boundary between two phases. Molecular dissociation of gypsum occurs almost instantaneously, so that dissolution is controlled solely by diffusion across the boundary layer. Dissolution rates depend on boundary layer conditions and the concentration gradients across it; they are described by the following equation:

$$dC/dt = (KA/V)\,(C_s - C)^n$$

Where dC/dt is a rate of change of concentration in a volume V of solution with a bulk concentration C, Cs is the solubility of the dissolved substance, A is a surface area and K is a rate constant varying with boundary layer conditions, mineral properties and surface roughness.

Theoretical and experimental studies of the dissolution kinetics of gypsum and anhydrite are numerous, although many of the results are conflicting. The most comprehensive treatment of the topic is given in James & Lupton (1978) and James (1992). The brief summary below is based largely on these works.

The main difference in the dissolution kinetics between gypsum and anhydrite lies in the power of the term n. It was shown by Zdanovsky (1956), Liu & Nancollas (1971) and James & Lupton (1978) that the gypsum dissolution follows the first order equation, while the dissolution rate of anhydrite obeys the second order equation. The latter reflects partial control of the surface reaction rate, which is assumed to be hydration. Figure 9 shows this difference by plotting concentration against time, with an overlay of theoretical curves. For gypsum, the flow time (distance) at which solution approaches 90% of saturation is very short; the rate of dissolution decreases by several orders of magnitude above this limit. Similar dependence of gypsum dissolution rates on the saturation were reported by Laptev (1939), Kuznetzov (1947) and Pechorkin (1986). This fact

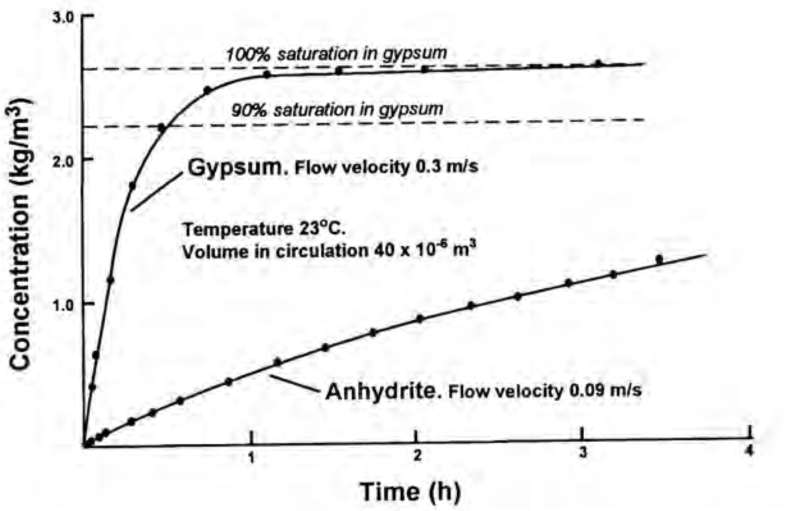


Fig. 9. Dissolution rates of gypsum (a) and anhydrite (After James & Lupton, 1978).

has important speleogenetic consequences (see Klimchouk, 1997, Chapter 6 in this volume).

The second order equation for the dissolution of anhydrite causes much lower dissolution rates. The travel distance for water flowing through fissures in anhydrite could be rather long before sufficient $CaSO_4$ is dissolved to precipitate gypsum. The conditions required for gypsum to be precipitated from solutions that have dissolved anhydrite are reached gradually due to the second order dissolution kinetics, but when they are achieved the precipitated gypsum may seal the seepage paths.

The main concern of dissolution kinetics studies are variations in K, which is not a true constant but one that varies with changing boundary layer conditions. These conditions affect the thickness of the layer, which varies with the flow velocity over the dissolving surface, the ionic strength of the solution and its temperature. The appropriate values of K that encompass these variables are considered briefly below, along with some other parameters, including the diffusion coefficient that reflects ion mobility (values for the common inorganic ions are rather similar). Theoretical calculations of rate constants for transport-controlled dissolution are rarely adequate and experimental data are used in most cases (Frank-Kamenetsky, 1987).

Gypsum and anhydrite, (which are polar molecules with strong electrical dipoles) tend to form thick boundary layers, which are thus easily subjected to thinning (stripping) by flowing water. This explains why K values and dissolution rates are strongly dependent upon flow velocities. Figure 10 shows linear dependencies for dissolution within a laminar flow regime; for each doubling of flow velocity over gypsum, K doubles, but for anhydrite it only increases by one and half times. Note that K has small positive values even in stationary water. Anhydrite shows a rapid increase in K with only a very small flow velocity. As a turbulent regime sets in, K is expected to

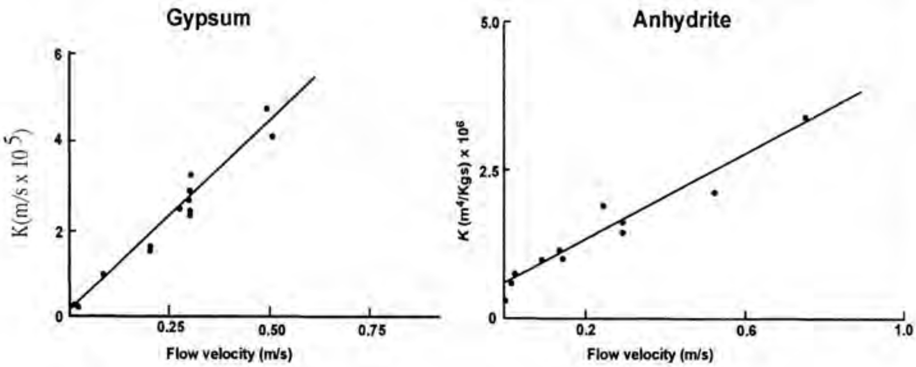


Fig. 10. The dependence of the rate constant for gypsum and anhydrite upon flow velocity (After James & Lupton, 1978).

increase abruptly, but there are no experimental data for gypsum. In the case of calcite an increase by a factor of ten is reported to occur. James (1992) postulates that gypsum and anhydrite should exhibit similar increases. The strong dependence of gypsum dissolution rates upon flow velocity has speleogenetic implications (see Klimchouk, 1997; Chapter I.6 in this volume). It also has a morphological expression manifested in a variety of dissolutional sculpting features that form readily on gypsum surfaces (see Sauro & Macaluso, 1997; Chapter I.8 in this volume).

The presence of other dissolved salts increases the ionic strength of a solution causing compression of the diffusion layer and hence raising K values. This is illustrated Table 2, which summarises data presented by James & Lupton (1978). The rate constant almost doubles for gypsum, but it increases by a factor of 9 for anhydrite, as the salt concentration rises from 0 to 10 g/L. Apparently, the effect needs to be allowed for when considering karst development in deep-seated settings, where a high content of sodium chloride ions commonly occurs. This is especially true if anhydrite rocks are considered.

Data on the temperature dependence of K for gypsum are given in Table 3. James (1992) suggests that a proportional relationship of log K to 1/T should be used to adjust K values from one temperature to another.

5. Gypsum-anhydrite-gypsum conversions

The thermodynamic stability and the solubility of gypsum and anhydrite are greatly affected by changes in the physical and chemical parameters that occur within common geological environments. The conversions of gypsum to anhydrite and back to gypsum are common processes.

Geological data suggest that in evaporitic environments at shallow depths sulphates occur mainly in the form of gypsum, but at depths exceeding 450m anhydrite predominates. However, there are numerous exceptions to this usual situation, with gypsum occurring at greater depths, and localised or dispersed anhydrite being found in the shallow sub-surface (for a brief review see

Table 2. The effect of sodium chloride on the dissolution rates of gypsum and anhydrite (After James & Lupton, 1978)

Concentration of NaCl, g/L	Gypsum: Kx10^5 (m/s)	Anhydrite: K ($m^3 kg^{-1} s^{-1}$)
0	1.5	0.45
10	2.9	0.77
30	3.2	1.7
100	5.8	5.8

Table 3. Variation of the rate constant of gypsum dissolution with temperature; flow velocity 0.25 m/s (After James & Lupton, 1978)

Temperature, C°	K x 10^5
5	0.8
15	1.7
23	2.6

Klimchouk & Andrejchouk, 1997; Chapter I.1 in this volume). Theoretical and experimental data on the stability of sulphate minerals and the mechanisms of conversions are also controversial, with some misleading views. This section discusses the modern understanding of the problem, which is important for the interpretation of karst processes and associated phenomena in gypsum and anhydrite.

The stability fields for gypsum and anhydrite are depicted in Figure 1. The presence of other salts, such as sodium chloride, also affects their stability and solubility. In evaporitic basins calcium sulphates primarily precipitate in the form of gypsum (Strakhov, 1962; Sonnenfeld, 1984). Anhydrite is believed to originate mainly by the dehydration of gypsum due to the effects of high pressure and temperature during burial. However, Sonnenfeld (1984) suggested that the factors of high pressure and temperature alone are insufficient to explain the transition of gypsum to anhydrite. He showed that gypsum dehydration occurs widely during early diagenesis, where it takes place at shallow burial depths, by interaction with hygroscopic brines of Na, Mg or Ca chlorides. James (1992) noted that in very hot climates gypsum can dehydrate to anhydrite when it is exposed at the surface, with to in excess of 42°C, or where highly saline water is present. These changes are slow and mainly unaffected by diurnal cycles, but over longer periods they can be affected by seasonal changes. It can be concluded that in such conditions the conversion will occur through the dissolution of gypsum and subsequent precipitation of anhydrite, not by alteration of the solid phase.

Regardless of how the anhydrite formed, most mature gypsum rocks appear to be secondary and to have formed by hydration of anhydrite to gypsum after uplift to shallow sub-surface levels. Consequently, the conversion of anhydrite to gypsum is a major significant process for karst development. It also has important implications for engineering and construction practices.

The common view is that the conversion of anhydrite to gypsum is accompanied by an overall increase in rock volume. Kushnir (1988) quoted an increase in rock volume of 18.25%, Pettijohn (1975), 30-50%; Gorbunova (1977), 64.9% and Ford (1989), 30-67%. Sonnenfeld (1984) quoted an increase of 61%, but stressed that a pressure of 60-150 kPa, corresponding to a 60-75m thickness of overlying rocks, would effectively balance the pressure generated by hydration and thus prohibit expansion. This effect is referred to widely in texts about karst (e.g. Jakucs, 1977). These argue that such expansion would seal most of the fissures in the gypsum/anhydrite rock, preventing water circulation and karst development. When expressed in this generalised form such views are misleading. Close examination of the problem reveals that expansion need not necessarily occur, and that a variety of mechanisms may be involved in the conversion processes. The problem is not clear theoretically, especially when rate processes are concerned, and the field data are controversial. Reported observations of heave and swelling, claimed to have resulted from the hydration of anhydrite, may relate to specific local conditions. Geological observations of folded structures in gypsum and the deformation of adjacent layers (assumed to prove expansion by anhydrite-gypsum conversion) may well be explained by other mechanisms (see Klimchouk et al, 1995 for an example). Furthermore, other field data show that in some underground and opencast anhydrite mines no heave has occurred (e.g. Kaiser, 1976; James, 1992). Experimental data and interpretation also conflict, suggesting that expansion during the conversion from anhydrite to gypsum is not always the rule.

Nekrasov (1945) derived an expression describing the limit of compression in a system Δ_{lim} caused by full hydration:

$$\Delta\text{lim} = (A/d_a + B) - c/d_c \qquad [5]$$

Where A is the quantity of the original substance of specific weight d_a, B is the quantity of added water (d=1) and C is the quantity of hydration product of specific weight d_c. A system will compress proportionally to the volume of water involved in the reaction; this means that changes depend on whether the process proceeds in an open or a closed system.

Theoretical calculations (Zanbak & Arthur, 1986; Pechorkin, 1986; Kushnir, 1988; James, 1992) suggest that when anhydrite converts completely to gypsum the molar volume of the solid phase increases by factor of 1.626, but the overall volume of the system reduces by 8.7%. Pechorkin (1986) reported experimental data for a closed system. He used 18-22 gram samples of anhydrite placed respectively in distilled water and in a saturated solution of $CaSO_4$. These were hermetically sealed for 1.5 years under normal pressure conditions. Complete conversion to gypsum occurred, resulting in a reduction in the overall system volume of 3% in the case of the distilled water and 2.8% for the saturated solution. Simultaneously, the solid volumes increased respectively by 3.1% and 4.1%. However, the short time reported for the complete conversion to gypsum apparently conflicts with another experiment performed by James (1992). He used a small disk of anhydrite immersed in water for 12 years. This displayed the growth of gypsum crystals on it, but it was not fully converted to gypsum.

In nature the mechanisms and rate of hydration of anhydrite to gypsum depend on many factors including: 1) the texture and structure of the rock, 2) the form and chemical composition of water coming into reaction and 3) the temperature and pressure conditions.

Most authors believe that hydration proceeds through the dissolution phase, so that anhydrite dissolves to provide a solution of $CaSO_4$ which then precipitates from solution as gypsum (e.g. Kuznetsov, 1947; Mossop & Shearman, 1973; Quinlan, 1978; Kushnir, 1988; James, 1992). However, Pechorkin (1986) argued that hydration through dissolution-precipitation accounts for only a minor proportion of re-hydrated rocks. He considered that the main process proceeded through the diffusion of water molecules (or hydroxyl ions) into the anhydrite crystal lattice; crystal lattice defects are said to favour this process. This is also supported by data suggesting that the crystal lattice defects in gypsum are inherited from anhydrite (Pechorkin, 1986). In reality, it is likely that the mechanisms of dissolution-precipitation and diffusion are closely interrelated.

There are two main types of water that are in contact with anhydrite rocks: 1) interstitial water, which is retained in pores within a rock and, 2) water that circulates freely, through joints and other partings. The former is disseminated throughout the rock mass, while the latter contacts only the surfaces of large rock blocks. The author believes that interstitial water plays the most important role in the hydration of anhydrite rocks, even though its volume is relatively small, due to the low porosity of anhydrite (note that not only the effective porosity, which is negligible in anhydrite, but total porosity should be considered). If fissuring within a deep-seated anhydrite is low, then such a system can be viewed as closed, with no additional water entering or leaving the system. When anhydrite is under thermobaric conditions in its stability region, the associated water saturated with $CaSO_4$ is in dynamic equilibrium with the mineral. When the rock becomes less buried and moves out of the stability field of anhydrite the equilibrium is disturbed and the interstitial solutions precipitate gypsum. In closed or semi-closed conditions only partial conversion may be achieved resulting in mixed anhydrite-gypsum rock, apparently with no expansion of the solid phase. Conversely, some shrinkage of the overall solvent-solid system may cause some water to be sucked from adjacent beds into the hydration zone. With continuing emergence of the rock to progressively shallower depths, imposed fissuring and free water circulation can result in open system conditions, allowing water to partially recharge the remaining pore spaces. In this situation, localised hydration along flow paths becomes increasingly important. Water circulation through open fissures in anhydrite and gypsum at shallow depths may be fast enough to ensure that dissolution will remove any excess gypsum. In this situation, no overall expansion of the rock may be expected to occur. The importance of the dissolutional removal of material is supported by the fact that the porosity of secondary gypsum is evidently higher when compared with that of anhydrite.

This explanation combines several possible hydration mechanisms and encompasses most of the known geological peculiarities of gypsum-anhydrite formations. It suggests that, in natural conditions, the mechanisms and rates of anhydrite to gypsum conversion depend on the tectonic regime, the water-bearing properties of surrounding sediments and both the regional and local flow regimes. It also suggests that, in most cases, no expansion in volume occurs during hydration. Expansion resulting in heave can be expected where thin layers of anhydrite are suddenly (in a geological sense) released from their confining pressure and exposed to water; perhaps a specific mode and rate of water ingress is required for expansion to occur. This view is in agreement with the occurrences of heaves definitely identified as being due to hydration of anhydrite to gypsum, which have been reported from tunnels or mines (James, 1992).

6. Recrystallization

Sulphate rocks undergo recrystallization throughout their diagenetic and catagenetic history. Evaporites precipitated from aqueous solutions contain connate pore water preserved from their original deposition. Some of these connate brines are expelled from the pores by compaction during burial, but some remain. When meteoric water begins to circulate through open partings, it can replace part of these interstitial connate brines and induce recrystallization. The gypsum-anhydrite-gypsum conversions discussed above further complicate the water-rock interaction. All these processes continuously disturb the water-rock equilibrium and are accompanied by recrystallization of the deposits.

Recrystallization considerably affects the various properties of gypsum and anhydrite by altering, among other things, a rock's texture and structure, porosity and strength. Consequently, it may influence karst development in many ways. Aggradation recrystallization is an important factor because generally the solubility of gypsum is higher for the smaller crystals. The different solubilities and dissolution rates for crystals of mixed size are the main cause of recrystallization and directly influence the karst process (see sub-chapter 2 above and Chapter I.3 below for details). However, the most important effect of recrystallization on karst is the alteration of the rock permeability. Two extreme examples are cited below to illustrate the possible effects.

In the Western Ukraine recrystallization has caused severe textural and structural differentiation of the buried gypsum sequence, with the formation of three distinct horizons (Klimchouk et al, 1995). This differentiation has also caused the formation of largely independent superimposed networks of lithogenetic fissures confined to each horizon. These fissure networks have served as primary paths for meteoric waters, which have entered the sequence from the underlying aquifer and circulated upwards under artesian conditions (Klimchouk, 1992). The structure of the lithogenetic fissuring was exploited by dissolution to generate the structure of huge maze cave systems. Thus, textural-structural differentiation of the gypsum by recrystallization was a primary guiding factor of this speleogenetic effect.

In Sicily, where gypsum massifs are exposed at the surface, a distinct crust, up to one metre thick, is formed and within this all the open fissures tend to seal (for details see Macaluso & Sauro, this volume; 1997). This is probably the result of gypsum recrystallization caused by the loss of interstitial water from the exposed rock, and by a specific set of dissolution-precipitation processes related to local climatic conditions. The exact mechanisms are not yet clear and need to be studied, but the effect upon karst development is obvious. The crust prevents the dispersed recharge of the gypsum massifs from the surface, and water is thus allowed to penetrate deeper into the gypsum only along selected major fissures and faults.

Another morphogenetic effect of recrystallization of the uppermost exposed layer is the formation of small ridges, blisters or tumuli, which occur where the crust coincides with the sedimentary bedding. These forms clearly result from the deformation of the geomechanically independent (detached from the substrate) outer layer by compressive stress, possibly caused by recrystallization. However, for expansional recrystallization to occur some specific conditions are required: 1) gaping bedding planes sub-concordant with the surface, 2) pathways for meteoric water to access the bottom of the outer layer and, 3) appropriate climatic conditions. Contraction and fracturing of the outer layer precede the expansional recrystallization, having first provided conditions 1 and 2 above. Meteoric waters, which escaped surface evaporation and run-off to the shallow sub-surface, are drawn continuously upwards back to the surface by capillary action through the pores in the outer layer, and this leads to aggradational recrystallization. The stresses generated by the volume expansion are released through swelling of the outer layer and manifested as ridges and blisters.

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Chapter I.3

DISSOLUTION OF GYPSUM FROM FIELD OBSERVATIONS

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Introduction

Studies of dissolutional denudation rates in limestone karsts are relatively numerous. Although there is a relatively long history of such studies, there are still many methodological problems involved, as is illustrated by the review provided by Ford & Williams (1989). Such problems are are not specific to limestone karsts; they are also relevant in the context of the estimation of gypsum dissolution rates, but to an even greater extent because of the higher dynamics, and hence the higher spatial and time-related irregularity, of gypsum dissolution. Furthermore, examples of regional estimates and field measurements of gypsum dissolution rates are relatively scarce.

There are two major approaches to the problem: 1) estimation of the rate of dissolutional denudation on the basis of determinations of solute load, and 2) measurement of dissolution rates on the basis of weight or volume loss of samples, or based on direct measurement of the micro-erosion due to dissolution. All these approaches have their own limitations, and the meanings of results obtained by different techniques are specific to the method, and thus cannot be compared directly.

Calculation of dissolutional denudation rates on the basis of solute load involves continuous monitoring of discharge and concentration parameters, and determination of value limits for the particular basin. All these characteristics are commonly obtained using a variety of methodologies, experimental designs and field installations, so that results from different regions are barely compatible. Furthermore, dissolutional denudation rate values derived from such studies give no, or few, data relating to the spatial distribution of the process throughout the 3-D karst system. The potentially great variety of dissolution rates between different environments (conditions of water-rock interaction) within a karst system cannot be revealed by studies of this sort.

Regional estimates of dissolution denudation rate values from solute load studies have been made for various gypsum karsts in the former Soviet Union and elsewhere, but they cannot safely be compared, due to differences of methodology and variable data quality. More detailed discussion of them provides little of relevance to the understanding of either the dissolution process itself or the evolution of karst forms.

The usefulness of dissolution rate values derived on the basis of weight or volume loss of samples, or by direct micro-erosional measurements, is limited mainly because their extrapolation through space is problematical. However, they do provide information that is valuable to the interpretation of dissolutional processes in particular environments, and in relation to karst form evolution. Such studies are more effective for gypsum than for limestone karsts because of the much higher characteristic dissolution rates, which make the errors involved in measurement relatively insignificant and allow the dissolution dynamics to be monitored, even over comparatively short timescales (Klimchouk & Aksem, 1985). These generalizations apply both to standard sample (tablet) methods and to micro-erosion meter (MEM) methods, which were initially developed for, and applied extensively to, studies of limestone dissolution rates (Gams, 1981; Dahl, 1967; Trudgill et al, 1981; Spate et al, 1985). Specific studies performed recently in the Ukraine, Italy and Spain have provided valuable information on the subject, and the results are reviewed generally in this chapter.

1. Field measurement of gypsum dissolution rates

Relatively many experimental studies of gypsum dissolution have been carried out in areas of different natural environment in the former Soviet Union (Skvortsov, 1955; Oradovskaja, 1962; Lukin, 1979; Pechorkin, 1969; Gorbunova et al, 1986, 1993). These studies were based on the weight loss of samples, but the samples were of different lithologies, sizes and shapes, and commonly the results were reported in terms of percentage weight loss relative to the initial sample. For these reasons it is difficult to derive sensible comparative values from the quoted results.

During the last decade, some research programs undertaken in the Ukraine, in Italy and in Spain have generated extensive datasets that support comparative consideration of dissolution rate values obtained from different environments and by different methods. These data are presented (see Table and Figure) and discussed briefly below, in order to derive a general view of gypsum dissolution rate characteristics under specific natural conditions. More detailed considerations are provided for the Ukraine by Klimchouk et al (1988, 1991) and for Spain by Calaforra et al (1993) and Calaforra (1996), and are partially published for Italy (Cucchi, Forti. & Marinetti, 1996).

Strictly speaking, supposed measurements of samples weight or volume loss, or MEM measurements of surface lowering, may reflect not only the effects of dissolution but also, to varying degrees, the effects of mechanical erosion. The latter effects can contribute greatly in high flow velocity environments, such as free-running streams. However, in most common environments (where the rock is exposed to precipitation at the surface, cave condensation, percolation water, in confined or unconfined aquifers) dissolution is assumed to be by far the dominant process affecting rock degradation, especially when considering gypsum, with its high solubility and fast dissolution kinetics.

1.1. Data from the Western Ukraine

Gypsum dissolution studies were performed in the Western Ukraine between 1984 and 1991, using standard tablet methods. Thirty-eight stations were chosen, representing different environments (situations of water-rock interaction) in the three major intrastratal karst settings: entrenched, subjacent and deep-seated (see Chapters I.4 and II.9). The following environments were studied:

1. Direct exposure to precipitation at the surface;
2. Exposure to cave air in zones of condensation;
3. Focused vertical percolation from overburden to gypsum (via vertical dissolution pipes) in

the vadose zone;

4. Unconfined aquifer in the lower part of a gypsum sequence, as represented by cave lakes;

5. Confined aquifer in gypsum, and in underlying basal sandy-carbonate beds (the water in the latter provides upward recharge to the gypsum). Tablets in this environment were placed by means of boreholes that were open within the appropriate part of the sequence.

Standard tablets 40 to 45mm in diameter, 7 to 8mm thick and weighing 18 to 25g, were made from a single variety of massive micro-crystalline gypsum of Miocene age. Control measurements were generally made every 3 months, but sometimes at other intervals ranging from 1 to 6 months, depending upon the actual dissolution dynamics and the accessibility of the sample. Measurements at most stations were supplemented by water sampling and subsequent determination of chemical composition and saturation index values with respect to gypsum. The dataset includes more than 500 measurements. Dissolution rate values that were originally expressed in units of mg cm^{-1} day^{-1} have been converted to mm a^{-1} (millimetres per year) units of equivalent lowering, to facilitate their comparison with other datasets.

1.2. Data from Spain

Between 1991 and 1994 a study of gypsum dissolution was carried out in the Sorbas region of Spain, involving both the standard tablet and MEM methods (Calaforra et al, 1993; Calaforra, 1996). During the first stage (1991-1992) tablets made from Ukrainian Miocene gypsum were used at 13 stations representing different environments, including:

1. Direct exposure to precipitation at the surface;
2. Exposure to cave air in zones of condensation;
3. Perched cave lakes with occasional sluggish through flow;
4. Ephemeral cave streams;
5. Siphon at the downstream end of the cave system (discharge).

For the second stage the program was expanded by installing more stations and by deploying tablets of different varieties of Messinian and Triassic gypsum from Italy, to facilitate study of dissolutional effects upon different lithologies. Control measurements were carried out every 3 months. Additionally, 22 MEM stations operated between 1992 and 1994, at sites representing environments 1, 2 and 4 listed above.

1.3. Data from Italy

Between 1993 and 1995, gypsum dissolution rates were measured by means of the micro-erosion meter (Dahl, 1967; Forti, 1981; Trudgill et al, 1981; Spate et al, 1985) in surface environments suffering direct exposure to precipitation. The field experimental stations (providing measurements from natural gypsum exposures) were located in 17 different areas on natural gypsum outcrops of 10 different gypsum lithologies, to assess a variety of morphological and climatic conditions within the range from 47° to 36° latitude, with annual average rainfall values between 300 and 1,350mm a^{-1}. Measurements were also carried out on samples of 12 different gypsum lithologies exposed in 7 field laboratories. The resulting dataset includes more than 3,000 measurements.

Table

Gypsum dissolution rates in different regions and environments

N. of data set	Region	Method, environment	Dissolution rate, mm a-1			Source
			Variations from	to	Average value	
1.	Russia, pre-Urals	VL, river waters	-79.35	-190.44		Pechorkin, 1969
2.	Russia, pre-Urals	RM, river waters	-200	-3000		Pechorkin, 1986
3.	England, Ripon	RM, river waters	-100	-200		James, 1992
4.	W. Ukraine	TWL, surface, samples exposed to precipitations, SIgyp -4.38	0	-1.5	-0.25	Klimchouk et al., 1991
5.	Italy	MEM, surface, outcrops exposed to precipitations, data from field stations	-0.31	-1.42	-0.60	Cucchi, Finocchiaro & Forti
6.	Italy	MEM, surface, samples exposed to precipitations, data from field labs	-0.20	-1.33	-0.71	Cucchi, Finocchiaro & Forti
7.	Italy	MEM, surface, rocks exposed to precipitations, Triassic gypsum	-0.60	-1.15	-0.78	Cucchi, Finocchiaro & Forti
8.	Italy	MEM, surface, rocks exposed to precipitations, Messinian gypsum	-0.20	-0.91	-0.61	Cucchi, Finocchiaro & Forti
9.	Spain, Sorbas	TWL, surface, samples exposed to precipitation	0	-1.54	-0.28	Calaforra, 1996
10.	Spain, Sorbas	MEM, surface, outcrop exposed precipitations	-0.02	-0.53	-0.42	Calaforra, 1996
11.	W. Ukraine	TWL, focused percolation in the vadose zone (vertical pipes), SIgyp -0.13	0	-1.52	-0.66	Klimchouk et al., 1991
12.	W. Ukraine	TWL, unconfined aquifer (cave lake), upper layer, SIgyp -0.21	-3.22	-18.17	-10.40	Klimchouk et al., 1991
13.	W. Ukraine	TWL, unconfined aquifer (cave lake) bulk water, SIgyp -0.002	-0.05	-6.16	-1.12	Klimchouk et al., 1991
14.	Spain, Sorbas	TWL, perched cave lakes with temporal sluggish through flow	0	-0.30	-0.03	Calaforra, 1996
15.	Spain, Sorbas	TWL, temporal stream in a cave	0	-0.87	-0.05	Calaforra, 1996
16.	Spain, Sorbas	MEM, temporal stream in a cave	+0.07	-0.40	-0.16	Calaforra, 1996
17.	Spain, Sorbas	TWL, Siphon at the downstream end of the cave system (discharge)	0	-0.2	-0.02	Calaforra, 1996
18.	W. Ukraine	TWL, confined aquifer in gypsum, natural conditions, SIgyp -0.21	-0.16	-1.22	-0.22	Calaforra, 1996
19.	W. Ukraine	TWL, confined aquifer in gypsum, disturbed conditions, SIgtp -0.05	-0.26	-3.46	-1.56	Klimchouk et al., 1991
20.	W. Ukraine	TWL, confined aquifer below gypsum (recharge to the gypsum), SIgtp -1.48	-2.48	-25.57	-14.54	Klimchouk et al., 1991
21.	W. Ukraine	TWL, cave air	+0.03	-0.03	-0.003	Klimchouk et al., 1991
22.	Spain, Sorbas	TWL, cave air	0	-0.03	-0.004	Calaforra, 1996
23.	Spain, Sorbas	MEM, cave air	+0.09	-0.45	-0.10	Calaforra, 1996

Methods: RM = retreat measurements, VL = volume loss, TWL = tablet weight loss, MEM = micro-erosion meter.

1.4. Other data

Three datasets chosen from other occasional field observations of gypsum dissolution that are scattered through the literature appear to be convertible into units that allow their comparison. They all represent the active surface river flow environment, which is analogous to the case of allogenic recharge of a karst system. These data are based on measurement of the dissolutional retreat of boulders submerged in river water, and the cutting back of gypsum cliff faces and fissure walls in cliffs under the action of flowing water.

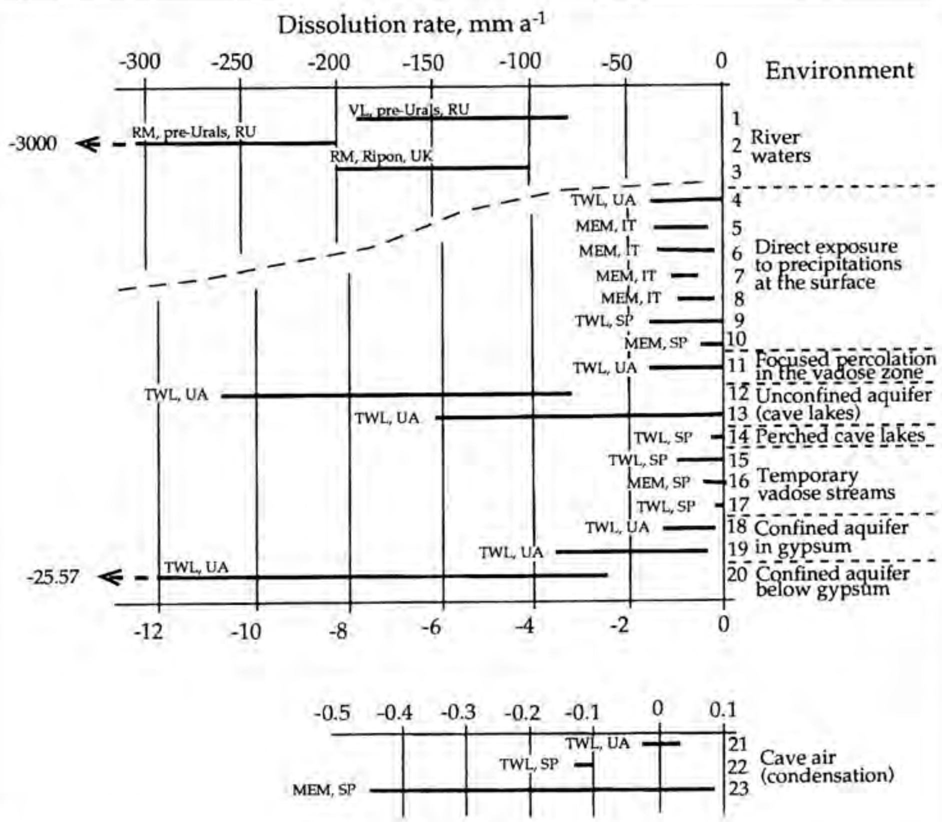

Fig. 1. Gypsum dissolution rates in different regions and environments. Numbers on the bars correspond to the dataset numbers in the Table. Methods: RM = retreat measurements, VL = volume loss, TWL = tablet weight loss, MEM = micro-erosion meter.

2. Dissolution of gypsum in different environments

The Table and Figure below provide generalized summaries of the above datasets, grouped to represent different environments and experimental methods. The dissolution rates are characterized by minimum, maximum and average values. Most groups include data from several stations. It should be noted that average values do not provide a consistent reflection of what they might appear to represent, due to the different ways in which they were determined. Some are values that average a number of individual measurements from one (at different control periods) or more stations (different control periods and different locations), while others represent averages for a complete dataset, average values derived from individual stations (as in the case of the Italian dataset), or values measured (in the case of MEM) or calculated (from the cumulative weight loss of tablets) for a long period encompassing several intermediate control periods. Moreover, though the MEM lowering values are based on direct measurement, the values derived from tablet experiments represent calculated equivalent lowering. In addition, some environments (stations) demonstrate seasonal variability of rates that reaches one or even two orders of magnitude, and this variability increases with decreasing control intervals. These points reinforce the warning expressed by Ford & Williams (1989) that there is a need for great caution in attempting the interpretation and extrapolation of results through time and space. Finally, it must also be stressed that the dissolution rates discussed here have nothing to do with the geomorphological concept of overall surface lowering.

2.1. Localized surface flow (river waters)

Pechorkin (1969) reported dissolution rate values ranging from 79.35 to 190.44mm a^{-1}, that were derived from a five-year-long observation of specific gypsum boulders in a small gulf of the Kama river reservoir, in the pre-Urals, Russia. Another estimate from the same reservoir represents the rates of fissure widening in a gypsum cliff, and ranges between 200 and 3,000mm a^{-1}, depending upon the fissure orientation relative to flow, and hence upon the actual flow velocity (Pechorkin, 1986). Gypsum dissolution rates by river water were also derived from long-term observations of the rate of undercutting of a gypsum cliff face on the river Ure, near Ripon, England. The recorded values, between 100 and 200mm a^{-1}, were confirmed by calculations based on observations of a dissolving gypsum block in the same river (James, 1992). All three of these estimates are largely coincident, though the upper limit of fissure widening in the Kama river cliffs seems to be an overestimate, or may be related to special local conditions.

2.2. Direct exposure to precipitation

This environment is characteristic of all the Italian datasets, which are derived from a wide range of climatic conditions, ranging from semi-arid (490mm a^{-1} of precipitation) in Central Sicily, to Mediterranean and tending towards continental in the Trieste area (with 1,350mm a^{-1} of precipitation. This is supplemented by data from the arid Sorbas area in Spain (250mm a^{-1} of rainfall, 80% of which occurs on only 3 to 4 days), and from the temperate continental Ukraine (640mm a^{-1} of precipitation, 20-25% of which is in the form of snow).

Comparison between the MEM and tablet method is possible only on the basis of data from the Sorbas area, where both techniques have been used (datasets 9 & 10). The tablet method shows values roughly 1.5 times greater than the MEM, both for the maxima and the averages. However, the method factor does not account entirely for this difference, as the measurement periods of each method only overlap partially; the total rainfall in 1992 (the principal year of the tablet exposure) was much lower than in 1993, when most of the MEM measurements were carried out.

Differences between minimum and maximum values are up to two orders of magnitude for the Ukraine and Spain, and 4.6 to 6.6 times for Italy (datasets 5 & 6). The lower variation apparent in Italy is explained by the fact that the range is based on averaged values from a number of stations, while the datasets from the Ukraine and Spain represent ranges of individual values (for intermediate control periods) from single stations.

Variations of average values between Italian stations, and of individual short-term values in the Ukrainian and Spanish stations, are strongly related to the amount of precipitation. The correlation between lowering (D, mm) and the amount of liquid precipitation for the corresponding period (W, mm) is 0.911 for the long-term set of Italian data from different stations, and 0.721 for the short-term set of Ukrainian data from a single station (in the latter case the data for intermediate control periods are analyzed). The relationships are approximated by the following equations:

Italy: $D\ (mm) = 0.000725 * W\ (mm) + 0.1815$

Ukraine: $D\ (mm) = 0.000476 * W\ (mm) - 0.0429$

It is remarkable that the extreme and average values of dissolution rates obtained from the tablet method in the Ukraine (dataset 4) and in the Sorbas area of Spain (dataset 9) are essentially the same, despite the striking climatic differences. This can be explained partially by acknowledging that snow precipitation in the Ukraine has little dissolutional effect on tablets. The average dissolution rate values from the Italian datasets are 2.5 to 3 times higher than those from the Ukraine and Spain.

The Italian data demonstrate that the differences between MEM measurements at field stations (exposed rocks faces; dataset 5) and at field laboratories (exposed gypsum samples; dataset 6) are relatively insignificant when compared to the variations between stations (climatic conditions). Triassic gypsum (dataset 7) dissolves more readily than Messinian gypsum (dataset 8), though again, the difference appears to be lower than the typical variations between localities.

2.3. Focused percolation in the vadose zone

Situations where focused downward percolation water enters gypsum beds from overlying formations are typically found in entrenched intrastratal karsts. Such percolation is responsible for the development of characteristic vertical dissolution pipes in gypsum (see chapters I.5 & I.9). Gypsum dissolution in this environment has been studied at several stations in the Western Ukraine. The dissolution rate values vary greatly between stations and seasons, reflecting the highly irregular percolation regime and the local peculiarities in water-rock interaction conditions. The data included in the Table (dataset 11) correspond to conditions where dripping water flowed for about 1 to 2m along the gypsum walls in the upper part of a pipe before coming into contact with a tablet.

2.4. Unconfined aquifer in gypsum

This environment has been studied at four stations in the Podols'ky region of the Western Ukraine, where the lower part of the gypsum sequence forms an unconfined aquifer within wide inter-valley massifs. The aquifer is characterized by hydraulically interconnected cave lakes (with a sluggish regional flow) that are located in the lowermost parts of the cave systems. These lakes are also connected hydraulically to the underlying basal sandy-carbonate aquifer. Hydrochemical studies suggest that there is a distinct stratification of the lake water due to the effects of gravitational separation. The average TDS content (mainly sulphates) changes from 1.42g L^{-1} in the uppermost water layer to 2.13g L^{-1} in the bulk water below a depth of 20 to 25cm. There is a corresponding decrease of average saturation index with respect to gypsum from -0.21 to -0.002. Stations with tablets within the uppermost layer demonstrate relatively intense dissolution (rates ranging from - 3.22 to -18.17; average -10.40mm a^{-1}), while dissolution rates in the bulk water are commonly about ten times lower (ranging from -0.05 to -6.16 mm a^{-1}, with an average value of -1.12mm a^{-1}). Variations, which are particularly noticeable in the bulk water, are not time-related, but spatial (between different stations), reflecting different intensities of circulation in individual lakes. Recorded seasonal variations are small and display no obvious regularities, though dissolution rates in the uppermost layer have demonstrated significant fluctuations between some years. For instance, the average value for 1995 (6.35mm a^{-1}) was roughly half of those recorded for 1995 and 1997 (12.30 and 13.50mm a^{-1} respectively).

2.5. Perched cave lakes

Results relating to lakes perched in the vadose zone were provided by three tablet stations in the Sorbas area of Spain, where intermittent through-flow occurs during sporadic rainy periods. The average dissolution rate of this environment (0.03 a^{-1}; dataset 14) is not quite representative, because dissolutional activity is minimal during most of the year, but greatly enhanced during short periods of rain and concomitant through-flow.

Some cave lakes in the Western Ukraine are perched on clayey fill, and not connected to the aquifer. This is an environment of almost stagnant water, with TDS content of 2.0 to 2.5g L^{-1} and SIgyp that fluctuates close to zero, commonly assuming positive values. Dissolution rates (not included in the Table) vary slightly below and above zero, between limits of -0.01 to +0.01 a^{-1}.

2.6. Ephemeral streams in caves

It is difficult to interpret dissolution rates in free-running cave waters due to highly irregular flows and chemical regimes. In the Sorbas area of Spain through-flow in gypsum occurs only after infrequent rainfall events. The tablet station in this environment produced highly variable values of intermediate (3-monthly) measurements ranging from 0 to -0.87mm a^{-1}, with an average rate of -0.05mm a^{-1}. The highest recorded rate is the lowering equivalent of the tablet weight loss during a 3-month period, within which most of the dissolution was associated with a single rainfall event (120mm of rain during 24 hours). Assuming that 90% of the measured dissolution occurred during 3 days of high flow related to that event, then the calculated dissolution rate value of - 180.1mm a^{-1} is compatible with dissolution rates for surface river water.

MEM measurements in the same environment display smaller dissolution rate variations (+0.07 to -0.40mm a^{-1} ; the former value indicating deposition, perhaps of $CaCO_3$), and a higher average value of -0.16mm a^{-1}.

It is remarkable that even at the downstream end of the cave system, in a siphon located close to the discharge point of the Cueva del Agua, notable dissolution has been recorded, averaging - 0.02 mm a^{-1}.

2.7. Confined aquifer in gypsum

This environment can be regarded as the most significant in terms of dissolution rates within gypsum karst, considering that intrastratal deep-seated and subjacent karsts are the predominant gypsum karst types (see Chapter I.4). It has been studied extensively in the Western Ukraine, where a confined aquifer in gypsum is connected hydraulically with, and receives its recharge from, the underlying regional sandy-carbonate aquifer. Water in the gypsum attains varying dissolved sulphate concentrations, depending upon the intensity of cross-formational circulation and the configuration and "maturity" of the cave systems in the gypsum. This explains why water chemistry and dissolution rates may vary substantially between localities (boreholes) even within a single area. The variations referred to below reflect such spatial differences. Groundwater dynamics and chemistry do not display notable seasonal variations under such conditions.

Nine stations in the Nikolaevsky area are characterized by an average TDS content of water of 1.36g L^{-1}, SIgyp -0.21, and gypsum dissolution rates varying from -0.16 to -1.22mm a^{-1} , with an average value of -0.22mm a^{-1}. In the Jazovsky area (3 stations) the average TDS content is higher, and SIgyp is lower than in the above area (1.82g L^{-1} and -0.06 respectively), but the gypsum dissolution rates are substantially higher (varying from -.026 to -3.46; average -1.56mm a^{-1}). Hence, despite the hydrochemical conditions seeming to be more favourable for gypsum dissolution in the Nikolaevsky area, the average dissolution rates are seven times higher in the Jazovsky area. This can be explained by the hydrodynamic conditions being severely disturbed within the Jazovsky area, where massive underground water abstraction occurs throughout the year to provide de-watering of a large open-cut sulphur mine (see Chapter I.9), resulting in substantial increase of flow velocities. Data of numerous tracing experiments conducted by A.. Klimchouk and S. Aksem (unpublished) suggest that flow velocities in the confined aquifer range between 25 and 77m day^{-1} under natural conditions in the Nikolaevsky area, while they range between 400 and 2,500m day^{-1} in the Jazovsky area. More substantial lateral flow component within the gypsum may account for higher sulphate concentrations in the Jazovsky area, but higher flow velocities cause greater dissolution rates there, as compared with the Nikolaevsky area. The above dissolution rate results demonstrate a great influence of flow velocities on dissolution rates in gypsum, through changing the rate constant K term (see section 4 in Chapter I.2).

Data from another three tablet stations in the Jazovsky area characterize gypsum dissolution in waters of the sandy-carbonate aquifer, which underlies the gypsum sequence in the Western Ukraine. These data correspond to the situation where water dissolves gypsum along the lower contact of the stratum, and/or enters the gypsum via fissures. Waters in the basal aquifers, with a TDS content ranging from 0.4 to 0.6g L^{-1} and average SIgyp = -1.70, dissolve gypsum at rates ranging between -2.48 and -25.57mm a^{-1} (average value = -9.16mm a^{-1}).

2.8. Cave air

As condensation in cave air is regarded as being an important speleogenetic agent (see Chapter I.5), it was appropriate to attempt to study dissolution rates for gypsum exposed to cave air in zones where apparent condensation occurs. This was done using tablets in the Western

Ukraine (dataset 21) and using tablets and MEM in the Sorbas area of Spain (datasets 22 and 23). The data from tablets are essentially the same from both regions. The difference between extreme values fully corresponds to seasonal variations (this also applies to data from the MEM method). At stations within transitional zones between external and internal climates higher rates are recorded for warm periods, while during cold periods neither dissolution nor precipitation takes place. This agrees perfectly with the theoretical course of condensation processes (see Chapter I.5). However, data from one station within the local condensation zone in the deep internal part of the Optimisticheskaja maze cave in the Western Ukraine, display the opposite trend. Condensation there is caused by air exchange between two extensive cave series through a single passage; this exchange is governed by rules that differ from those governing interaction between external and cave atmospheres.

The dissolution rates obtained for this environment by MEM measurements are much higher than those from tablets. This can perhaps be explained because condensation occurs more intensely on the surface of the host rocks than on small samples, which tend to equilibrate more rapidly to the temperature of in-flowing air.

3. Additional discussion and conclusions

The recent studies described above provide important information on gypsum dissolution rates in common natural environments. There are dramatic rate variations between different environments, many of which are also characterized by high rate variations with respect to time.

Dissolution rates of gypsum and carbonates can be compared directly when obtained by the same method under the same conditions, as in the field laboratory in Trieste, Italy, where both carbonate and gypsum samples have been exposed to precipitation. The results suggest that average rates of dissolution of gypsum samples (0.68 to 1.14mm a^{-1}) are roughly 30 to 70 times greater than dissolution rates of carbonate samples (0.010 to 0.035mm a^{-1}), which agrees broadly with theoretical expectations.

Karstological interpretations of the dissolution rate data should take into account a spatial distribution of certain conditions of water-rock interaction within a karstified formation. This depends largely upon hydrogeological settings and types of karst according to its evolution and the presence of cover-beds. The typology of karst is considered in Chapter I.4. Intrastratal karst is by far the predominant type of gypsum karst. There are no reliable data to allow evaluation of dissolution rates in its "young", deep-seated, sub-type. However, considering its poorly developed secondary porosity and sluggish flow conditions, relatively low dissolution rates and, consequently, prolonged time-spans for initiation and early development of karst systems can be assumed. In shallower artesian conditions, where flow is considerably intensified and karst systems are already quite well developed, dissolution rates are high, as evidenced by the data from the Western Ukraine. Considering these high rates, which are relatively uniformly distributed through the well-developed surface of hydraulically open paths in and around gypsum, such an environment can probably be regarded as that experiencing the most intense karstification. There should be no significant climatic and seasonal variability of dissolution rates in this environment.

In karst types with extensive vadose zones and unconfined aquifers (intrastratal entrenched and exposed karst types), dissolution within the rock becomes highly localized along certain percolation or free-running flow paths, and along the water table zone. Despite rates being locally high, such dissolution does not contribute much to overall karstification processes. Intrastratal entrenched karsts, where gypsum is areally protected by some degree of cover, can survive through quite prolonged geological timescales, producing spectacular karst landscapes due to focused morphogenesis. Localized dissolution plays a major part in karst morphogenesis, creating characteristic underground and surface forms.

Exposed gypsum massifs are subjected to intense dissolution, distributed relatively uniformly across the external surface; this is another environment of intense overall karstification. When exposed to meteoric agents in climates that provide a substantial amount of liquid precipitation, gypsum outcrops probably cannot survive for more than few hundred thousand years. This agrees with the observed fact that exposed gypsum karsts are not common in areas of temperate and humid climate. Dissolution rates in this environment are prone to large seasonal variations.

Condensation waters may produce substantial dissolution in ventilated karst massifs. However, condensation is not spread uniformly throughout the caves, but is localized mainly within transitional micro-climatic zones near the surface, and occurring mainly during the warm seasons. Although dissolution caused by condensation may have a speleo-morphogenetic role, it cannot be regarded as an important factor in karst development.

Localized free-running water, such as allogenic rivers or local streams formed on poorly fissured gypsum outcrops or on remnants of insoluble sediments, dissolve gypsum at extremely high rates. Clearly, the cutting down of a gypsum sequence, or the development of a through-cave passage by such streams should be a geologically instantaneous event. However, this dissolutional environment is so localized spatially that it does not contribute notably to overall karstification.

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Chapter I.4

THE TYPOLOGY OF GYPSUM KARST ACCORDING TO ITS GEOLOGICAL AND GEOMORPHOLOGICAL EVOLUTION

Alexander Klimchouk

"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 implicitely 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 definition. 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 subsurface 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 intrastratal 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-syndepositional 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

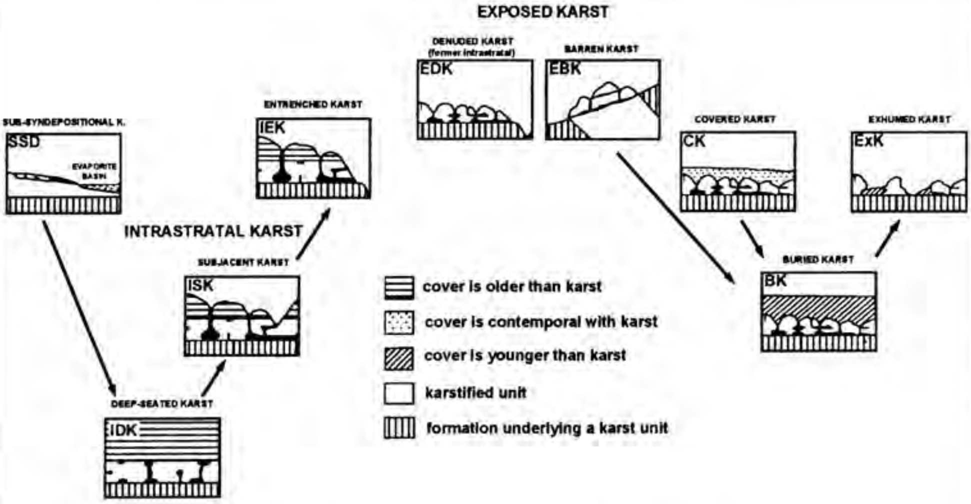

Fig. 1. Types of karst according to its evolution and stratigraphical position.

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-syndepositional 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-syngenetic 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 then 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 then 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 I.5 & I.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 I.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 I.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 I.2 and I.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 authochtonous 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 unsoluble, 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 monoclinal 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 monoclinal 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-syndepositional 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 I.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 exumed and re-integrated into active systems. However, as noted above, gypsiferous rocks rarely survive through the full succession of karst stages.

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Chapter I.5

SPELEOGENESIS IN GYPSUM

Alexander Klimchouk

Satisfactory explanation of the origin and development of caves (speleogenesis) is a core problem of karst studies. Karst evolves as a circulation system, organised and interconnected through a conduit structure. Such a system may include superficial inputs and outputs, expressed as or related to karst landforms. However, there may be no such components if the system is represented entirely by conduits as in the case with deep-seated intrastratal karst.

The main differences between speleogenesis in gypsum and in carbonate rocks lie in the chemistry and kinetics of their dissolution, in some of the lithological or structural peculiarities of the respective rocks and formations, and in their hydrogeological characteristics. These sets of factors are examined in detail in chapters I.1, I.2, and I.6 respectively. The present chapter considers how these factors influence cave origin and development.

1. Caves in gypsum karst

Currently there are perhaps several thousand gypsum caves known around the word. In terms of the karst typology adopted here (see Chapter I.4), most of the caves that can be explored directly are found in exposed and intrastratal entrenched karsts. Caves are found more rarely in intrastratal subjacent karsts and are almost never found in deep-seated intrastratal karsts. The latter two karst types are by far predominant in terms of areal extent. It can be assumed that known caves represent only a very small portion of all the karst conduits and voids that occur within the upper few hundred metres of the geological sequence in gypsum karst areas. However, to justify the above statement, it must be demonstrated that caves are as common in deep-seated intrastratal karsts as they are in the entrenched and exposed types.

The world's largest currently known gypsum caves are listed in Table 1 Optimisticheskaja, the longest cave, is the second longest cave of any type known in the world. A striking gap exists between lengths of the three longest caves and the other caves in the list. The five longest gypsum caves, located in the Western Ukraine, account for well over half of the total known length of gypsum caves. This apparent bias is related partly to the unique structural prerequisites of speleogenesis, which are locally realised under artesian conditions. It also reflects a favourable regional evolution (with rapid uplift, and fossilization of labyrinth systems), the presence of overlying limestones, and considerable clayey protective cover (which prevented the infilling and/or destruction of the huge mazes). It is far more common, however, that artesian (intrastratal) caves in gypsum are partially destroyed while passing from conditions of intrastratal karst to those of entrenched and exposed karst. Moreover, all genera of caves in gypsum , whether relict or newly-formed, are more readily destroyed in exposed and shallow sub-surface environments than are those in carbonate karsts, due to the lower mechanical strength and greater inhomogeneity of gypsum forma-

Table 1a

Longest gypsum caves of the world (as for 1996)			
Name	Development, m	Country	Rock age
Optimisticheskaja	200000+	Ukraine	Neogene
Ozernaja	117000	Ukraine	Neogene
Zolushka	92000	Ukraine	Neogene
Mlynki	25000	Ukraine	Neogene
Kristalnaya	22000	Ukraine	Neogene
Kulogorskaja-1-2 - Troja	14100	Russia	Permian
Jester	11800	USA	Permian
Spipola-Aquafredda	10400	Italy	Neogene
Slavka	9100	Ukraine	Neogene
Agua, cueva de	8350	Spain	Neogene
Verteba	7820	Ukraine	Neogene
Cater Magara	7300	Syria	Neogene
Park's Ranch	6269	USA	Permian
Konstitutzionnaja	5880	Russia	Permian
Kungurskaya Ledjanaya	5600	Russia	Permian
Olimpijskaja	5500	Russia	Permian
Kumichevskaja	5000	Russia	Permian
Zolotoj Kljutchik	4380	Russia	Permian
Covadura	4245	Spain	Neogene
Crystal Caverns	3807	USA	Permian
Double Barrel	3724	USA	Permian
Scrooge	3700	USA	Permian
Umm al Masabih	3593	Libya	Jurassic
Leningradskaja	3400	Russia	Permian
Simfonia	3240	Russia	Permian
Pedro Fernandes	3204	Spain	Neogene
Pekhorovskaja	3180	Russia	Permian
Martin	3150	USA	Permian
Lomonosovskaja	3127	Russia	Permian
Carcass	2920	USA	Permian
Vodnaja	2900	Russia	Permian
Pinezhskaja Terehchenko	2600	Russia	Permian
Atlantida	2525	Ukraine	Neogene
Ingh. Ca' Siepe	2500	Italy	Neogene
Wimmelburger Schlotte	2840	Germany	Permian
Eras'kina 1-2	2500	Russia	Permian
10-years LSS	2450	Russia	Permian
Bukovinka	2408	Ukraine	Neogene
Hyaenenlabyrint	2310	Somaly	Paleogene
Severjanka	2300	Russia	Permian
Pekhorovskij Proval	2266	Russia	Permian
Kulogorskaja-5	2200	Russia	Permian
Geograficheskogo ob-va	2150	Russia	Permian
Ugryn'	2120	Ukraine	Neogene
Re Tiberio	2110	Italy	Neogene
Gostry Govdy	2000	Ukraine	Neogene

Table 1b: the world's deepest (>100m) gypsum caves (as of 1996)

The deepest gypsum caves of the word			
Name	Denivelation, m	Country	Rock age
Tunel dels Sumidors	210	Spain	Triassic
Pozzo A	>200	Italy	Triassic?
Corall, sima del	130	Spain	Neogene
Triple Engle Pit	130	USA	Permian
Covadura	126	Spain	Neogene
Campamento, sima del	122	Spain	Neogene
Aguila, sima del	112	Spain	Triassic
Rio Stella-Rio Basino	100	Italy	Neogene
AB 6	100	Russia	Jurassic

Note: The list has been compiled using data provided by Belski (for USA), Calaforra (for Spain), Forti & Sauro (for Italy), Kempe (for Germany), Klimchouk (for Ukraine), Woigt & Schnadwinkel (for Syria), Malkov & Lavrov (for Russia), Ehrsam (for Somaly)..

tions. These reasons also account for the relative scarcity of 20-80km-long gypsum caves, when compared with the full class of limestone caves. They also explain the generally much more modest sizes of the biggest chambers and passages in gypsum compared to those in limestones.

The common occurrence of caves under currently deep-seated artesian conditions is proven in many regions of intrastratal karst. Boreholes and mines have intersected large voids at depths below local base levels of 60 -100m (in the "artesian belt" of the gypsum karst in the Western Ukraine; see Chapter II.9), 300 - 400m (in the Pre-Urals, the Caspian depression, Russia; and the South Hartz region of Germany), or even deeper. Such deep-seated development is also evidenced by the presence of collapse forms, which have evolved after vertical through structures (see Chapter I.9) where gypsum lies at depths of several hundreds meters.

The deepest gypsum cave currently known (Tunel dels Sumidors, Valencia, Spain; see Chapter II.6) is only 210m deep, far shallower than the deepest caves in carbonate karsts. The main reasons are geological. In folded, mountainous regions, where the potential drained depth is greatest, gypsum formations are fragmented and do not favour the development of such vertically extensive sequences as do carbonates. Again, the lesser mechanical resistance and homogeneity of gypsum formations restricts the possibilities of deep gypsum caves developing and surviving.

Gypsum caves vary greatly in morphology. Particularly on the level of system patterns this commonly reflects, genetic differences. Several typical patterns can be distinguished:

1) Discrete, comparatively large voids, often isometric.

2) Rectilinear or ramifying mazes. Multiple storeys may complicate the structure;

3) Caves that are linear or crudely dendritic in plan and horizontal, inclined or step-like (with pits) in profile. Multiple storeys may complicate the structure;

4) Vertical pipes.

Development of these types of caves is related to particular speleogenetic environments and karst types (Table 2). Complicated evolution of karst systems may cause superimposition of diffe-

Table 2.

Genetic classification of caves in gypsum

TYPE OF KARST	SPELEOGENETIC SETTINGS			CHARACTERISTICS OF CAVES
	Hydro-geological conditions principal complementary	**Flow pattern through gypsum and type of recharge**	**Initial permeability (before speleo-genesis**	
Intrastratal deep-seated	confined (artesian)	1. Ascending flow, localized basal inputs	very inhomo-geneous, generally low to negligible, locally high	1. Discrete voids, com-monly large and isometric; associated stoping cavities in coverbeds at the top of VTS after breakdowns
		2. Ascending flow with possible lateral component, dispersed basal inputs	fairly homogeneous, generally low	2. Rectilinear 2-D or 3-D (multi-storey) mazes
Intrastratal subjacent	confined phreatic water table vadose	1. Ascending flow with possible considerable lateral component, localized or dispersed basal inputs		Continuing development of the types 1 and 2
		2. Descending flow with considerable lateral compo-nent, localized inputs from coverbeds and via super-ficial sink points; possible backflooding	heterogeneous: low to high	3. "Through caves": caves that are linear or crudely dendritic in plan, horizontal, inclined, or step-like in profile
				Enlargement of inherited caves at the water table
Intrastratal entrenched	phreatic water table vadose	1. Descending flow with possible considerable lateral component, localized inputs from coverbeds and via superficial sink points; possible backflooding	heterogeneous: low to high	Continuing or newly started development of the type 3 caves 4. Vertical pipes developing downwards from the top of the gypsum
Exposed denuded	phreatic water table vadose	1. Descending flow with possible considerable lateral component, localized inputs from coverbeds and via superficial sink points; possible backflooding		Continuing or newly started development of the type 3 caves
Exposed barren	phreatic water table vadose	1. Descending flow with possible considerable lateral component, localized inputs from coverbeds and via superficial sink points; possible backflooding		Continuing or newly started development of the type 3 caves

rent features and structures. Detailed characterisation of the above types of caves and their corresponding speleogenetic environments is given in sub-chapter 6 below. The suggested draft classification does not encompass all caves occurring in gypsum, but covers only those created by underground water circulation imposed upon aquifers. Other types include, for instance, cavities formed due to differential deformation of layers due to recrystallization ("tumulus"), or gravitational/tectonic caves formed, for example, due to unloading along escarpments.

2. Hydrographic (hydrodynamic) zones, artesian versus phreatic conditions

A long lasting controversy concerning the validity of vadose, water table and phreatic theories of cave development has been resolved during recent decades. The "four state" model of Ford & Ewers (1978) clarified the role of each corresponding environment. It is well accepted that most conduits originate under phreatic conditions, although their development or modification may continue at the water table or within the vadose zone (Palmer, 1984; Ford, 1988; Lowe, 1992). Some speleoforms may develop entirely under vadose conditions. However, a recently elaborated theory (Klimchouk, 1990, 1992, 1994, 1997a) suggests that caves may also originate and develop under artesian (confined) conditions and be subsequently modified in the phreatic, water table and vadose environments. Acceptance of these ideas allows the common confusion concerning the meanings of the terms "phreatic" and "confined" to be clarified.

In contrast to water-table or unconfined aquifer conditions, where the water table is under atmospheric pressure, the water pressure in a confined aquifer is greater than atmospheric at any point, as the head in such an aquifer is above the bottom of the upper low permeability confining bed. Any breaching of the upper confinement, such as by a well, a fault or a facial "window", will cause water to flow upwards to the level where the water column is high enough to balance the aquifer pressure (potentiometric level). This effect is mainly caused by water entering an aquifer at elevations greater than that of the base of the confining bed across most of the aquifer's areal extent, though there are other possible sources of pressure generation. Several confined aquifers may exist in a system, separated by poorly permeable beds. Confined aquifers are commonly called artesian aquifers, and confined conditions commonly referred to as artesian conditions.

The term phreatic implies conditions where water saturates all voids in a rock, in contrast to vadose conditions, above the water table, where voids are only water-filled transiently. Water in phreatic conduits is always confined by the host rock and possesses some hydraulic head above the conduit ceiling. This has given rise to some confusion where the terms "phreatic" and "artesian" ("confined") have been wrongly understood as being equivalents, especially when considering deep phreatic conditions. For example, Glennie (1954) termed water rising from such deep phreatic paths "artesian". Jennings (1971, p.97) noted that such usage is in a strict sense incorrect, but it serves as a reminder that consolidated rock can act virtually as its own aquiclude. It is necessary to distinguish the term "artesian" ("confined") as referring to flow conditions in a whole aquifer (or a system of aquifers where there is major geological confinement), rather then to flow conditions within a single conduit. Use of the term "phreatic" should be restricted to description of the lower zone in an unconfined aquifer, limited above by a water table that is free to rise and fall.

In hydrogeological terms, flow in artesian aquifers is considered to be: "...in many ways an extreme example of the effects found in the phreatic zone of unconfined aquifers, with the vertical hydraulic gradients increased as a result of the presence of the overlying confining bed." (Price, 1985, p.68). However, the fact that the distinction between phreatic and confined conditions is of ultimate importance for speleogenesis was not fully recognised in the past. The main difference is that in phreatic conditions discharge through a potentially developing flow path is governed by the resistance of the path itself, particularly of its narrowest part. In confined conditions discharge through conduits is governed by the resistance of the least permeable bed that causes major confinement of a system in the vertical down-gradient direction. This point is examined more fully in sub-chapter 5 below.

3. Implications of gypsum dissolution chemistry and kinetics

The chemistry and kinetics of gypsum dissolution have been considered generally in Chapter I.2. Important peculiarities affecting speleogenesis are:

1. The solubility of gypsum in pure water (2.531 g/L at 20°C) is roughly 10-20 times greater than the solubility of calcite in the presence of CO_2. In most relatively shallow environments (intrastratal entrenched karst, exposed karst) the influence of temperature variations is minor, but the effects of ion pairing, which increases gypsum solubility by up to 10%, must be considered.

2. Most commonly in deep-seated environments, but in subjacent karst settings too, several chemical and physical factors may (and in many regions are recorded to) increase or renew gypsum solubility considerably. The most important of these are: the presence of other salts in groundwaters (which enhances ionic strength and increases gypsum solubility by up to 3 times); anaerobic reduction of sulphates in the presence of organic matter; de-dolomitization of intercalated dolomite layers; and stress applied to the rock.

3. Whereas the kinetics of gypsum dissolution are described by the first order equation, anhydrite dissolution rates obey the second order equation. For gypsum, the flow time (distance) at which dissolution approaches 90% of saturation is very short; the dissolution rate decreases several orders of magnitude above this limit, and the 100% saturation level is approached asymptotically

4. Gypsum and anhydrite dissolution proceed even in contact with static water, but dissolution rates increase rapidly with increasing flow velocities. As a turbulent flow regime sets in, dissolution rates are boosted, probably by an order of magnitude.

5. The presence of other salts, such as sodium chloride, in solution considerably increases gypsum dissolution rates, but influences anhydrite dissolution rates even more drastically. This effect contributes particularly to speleogenesis in deep-seated environments.

4. Structural and hydrostratigraphical pre-requisites of speleogenesis

Initial permeabilities of common aquifers (e.g. some clastic rocks) in deep-seated settings is normally greater then that of karstifiable units, particularly sulphates, before the onset of speleogenesis. Gypsum beds commonly act initially as separating beds. Groundwater comes into contact with gypsum either from adjacent aquifer formations, or via minor beds of other lithologies, such as marls or dolomites, that are intercalated with the gypsum beds. This view is somewhat similar to that suggested by Lowe (1992) in his "Inception Horizon Hypothesis", although the intercalations in gypsum sequences do not commonly generate specific dissolution chemistry, as is suggested for carbonate sequences. However, such horizons in gypsum formations may locally determine chemical processes that maintain the gypsum dissolution potential, due to removal of sulphates from solution (sulphate reduction, de-dolomitization).

Late diagenesis (catagenesis) and/or tectonism impose fissure permeability upon gypsum formations, which then begin to play the major role in determining initial flow paths through the gypsiferous sequence. Gradient fields in confined conditions generally promote vertical, cross-formational circulation, although the presence of water-conducting intercalations and a specific fissure distribution may support a significant lateral component of speleogenetic development. While major tectonic fissures normally cut through the entire thickness of a bed, lithogenetic fissures tend to form largely independent networks that are confined within certain textural intervals. Such networks are characterised by a good lateral connectivity, but are connected vertically only at a relatively small number of discrete points. This provides the structural pre-requisites for the development of multi-storey maze caves (Klimchouk, 1992, 1994; Klimchouk et al., 1995; see also Chapter I.1).

5. Origin and development of conduits in confined and phreatic conditions

5.1. Origin and propagation of early conduits

A theoretical approach to the understanding of the propagation of early dissolutional openings in fissures has been developed by Palmer (1984, 1991), based on the combined consideration of mass-balance relationships, hydraulic equations for laminar flow, and chemical mass-transfer. Dissolutional enlargement of partings in soluble materials, gypsum in particular, has been investigated theoretically and experimentally by James & Lupton (1978) and James (1992).

It is generally believed that most proto-caves propagate through fissures where the connected apertures are small: limits between $<10\mu m$ to 1mm have been suggested (Ford & Williams, 1989). Recent study by Groves & Howard (1994) suggests that a minimum aperture of $100\mu m$ is required for conduit development. Seepage through them is very slow and laminar. The rate and configuration of dissolutional widening depends primarily on discharge through the fissure and the change in solute concentration along its length (Palmer, 1984, 1991; James, 1992). Due to gypsum's fast dissolution kinetics, solute concentration increases rapidly to about the 90% saturation level, so that the penetration distance, L_{90}, is quite short (for details of the L_{90} concept see Weyl, 1958; White, 1977; Ford & Williams, 1989). Fissures enlarge at their inlets, remaining almost unchanged downstream resulting in a tapered geometry. The mode of dissolutional enlargement of the fissure, or through a sequence of inter-connected fissures, will change only when a breakthrough of the penetration distance to the output boundary occurs, so that a flow path enlarges enough to permit an increase in flow velocity and penetration of significantly undersaturated water beyond the exit.

It is not yet clear whether the main breakthrough mechanism is the propagation of a taper

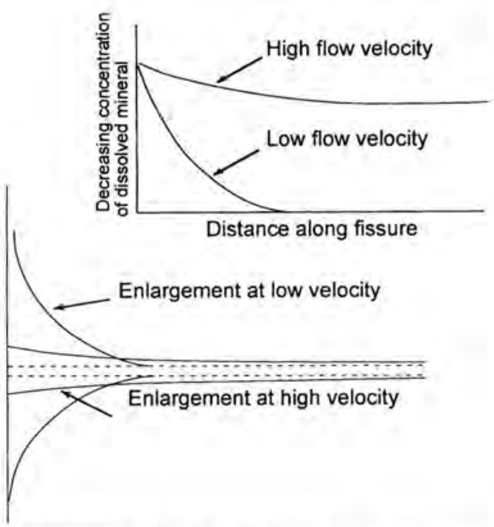

Fig. 1. Effect of flow velocity on enlarge-ment configuration (After James & Lupton, 1978).

from the input end, or slow dissolutional enlargement along the entire fissure length by water close to saturation. Shapes of enlarged fissures depend upon rock solubility, the dissolution rate constant, and flow velocity. Other variables being equal, fissure enlargement at the input end will be more tapered in gypsum than in limestone due to faster dissolution kinetics. Lower initial velocities produce sharp tapers, whereas higher velocities promote a more gradual enlargement (Fig.1). The sensitivity of the enlargement configuration to flow velocities, and hence to differences in the initial fissure width, should be more pronounced in fissures in gypsum than those in limestone.

Under sluggish flow conditions in gypsum it seems possible that the tapering is so localised that the first part of a fissure may reach human-penetrable sizes, while its downstream parts remain almost unchanged and very narrow. The common occurrence of "blind" ends of dissolutional passages in the labyrinthine caves of the Western Ukraine, with narrow guiding fissures recognizable along their apex, supports such an assumption. This introduces some potential confusion of the morphometric criteria that allow distinction between the inception and development stages in gypsum speleogenesis.

The duration of the initiation phase (until breakthrough is achieved) depends mainly on the length of fissure paths and on initial flow rates; the latter in turn depends strongly upon the width of the initial aperture (it is proportional to the cube of the width). This dependence is the primary factor responsible for the selective enlargement of openings (Fig. 2). The effect is more pronounced in gypsum than in limestone due to diffusion control of dissolution kinetics, which causes stronger dependence of the dissolution rate constant upon flow velocity. It is quite possible that duration of the initiation phase of conduits propagating through narrow fissures in gypsum is comparable with, if not longer, than that in carbonates, given that the boundary hydraulic conditions are equal. This apparent paradox is caused by dissolution kinetics being faster in gypsum than in carbonates.

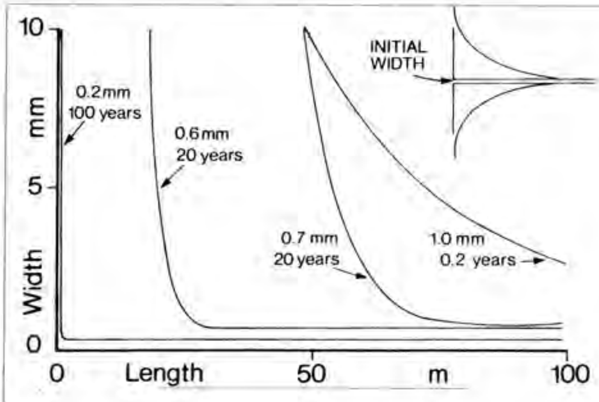

Fig. 2. Penetration distances or progress of the dissolution front for - L_{90} in massive gypsum, calculated for initial fissure widths ranging from 0.21 - 1.0mm. Time elapsed since initiation is in years. The hydraulic gradient is 0.2 and water temperature is 10°C. Inset: the form of the dissolution taper into the fissure that is obtained from theoretical calculations such as these (After James & Lupton, 1978, as adapted by Ford & Williams, 1989).

5.2. Development of conduits

At this point the distinction between phreatic and confined conditions becomes crucial to speleogenetic development.

Phreatic conditions. The controls of conduit development under phreatic conditions are best described by Palmer (1984, 1991). Given a substantial hydraulic gradient, the amount of flow through a fissure path is determined by its width. During the initiation stage water emerging at the output boundary is almost saturated, so that the rate at which any route enlarges depends upon the amount of flow rather than upon dissolution kinetics (discharge-controlled stage). For a given conduit, enlargement rates increase slowly, as the discharge through the path is severely restricted by the narrower downstream parts. When breakthrough of L_{90} has occurred, enlargement accelerates dramatically and promotes a further large increase of discharge, so that a "runaway" condition develops. Enlargement rates in gypsum are further accelerated as turbulent conditions set in due to the mass transport control of dissolution kinetics. Those conduits that achieve early breakthrough are able to increase their discharge either by capturing water from neighbouring conduits or by extending their primary catchment. This situation emphasizes the importance of initial differences in hydraulic efficiency between fissures, and also explains the competitive early development of conduits.

However, this is already the stage when dissolution kinetics take control of enlargement. It is demonstrated (Palmer, 1984) that the enlargement rate of conduits in limestones does not increase in an unlimited way, but levels off at a maximum that is roughly of the order of 1mm per year. From then on, all successful conduits enlarge at almost identical rates. Such a limit has not been derived for gypsum by calculations, but it can be assumed that it is much higher than for limestone and is not achieved within reasonable flow rates. In most cases conduits in gypsum will continue to grow at accelerated rates until discharge is able to grow. For conduit growth in gypsum, the higher solubility of the rock and faster dissolution kinetics mean that the development stage in unconfined settings is much shorter than in the case of carbonate speleogenesis. The "runaway" development and competition of alternative flow paths under phreatic conditions are better expressed in gypsum than in limestones. This is the main reason for linear phreatic caves with poorly developed side passages being so typical within gypsum karst (see section 6.3).

When conduit enlargement is sufficient to carry more water than a catchment can deliver, the system switches to catchment control, and water table/vadose conditions are established (Palmer, 1984). In unconfined gypsum karst settings most active conduits adjust their sizes rapidly to accommodate the highest possible discharge (Forti, 1993), so that floods due to passage constrictions rarely occur in gypsum caves.

Confined conditions. The typical architecture to be considered comprises two "normal" (non-karstic) aquifers separated by a gypsum unit with fissure permeability, with the whole system confined by an upper, non-karstifiable, aquitard (Fig.3). Some vertical upward head gradient between the aquifers exists, and there is slow discharge from the system through the upper confining bed along structural weaknesses.

The head gradient between the lower and upper confined aquifers drives a slow flow through connected fissure paths. Initiation is slow, with wide tapers at the inputs to the fissures and abrupt terminations at the propagation front. When breakthrough occurs, the successful path increases its discharge to some extent, but initially not significantly. This is because flow through the system is governed (restricted) by the resistance of the upper confining bed, rather then by the available recharge, as in phreatic conditions. Increase in the path width after breakthrough locally minimizes the head gradient between the confined aquifers, so that the flow through it does not increase dramatically. It is then governed solely by the transmissivity of the upper confining bed, which is roughly constant and normally low. The fundamental difference between artesian and phreatic speleogenesis is that in the former case there is no dramatic boost in conduit enlargement rates to compare with that experienced under phreatic conditions (Fig. 4). The dynamics of conduit growth differ little between the initiation and development phases, and competitive development, common under phreatic conditions, is inhibited in artesian settings.

The development of conduits under confined conditions is rather slow and uniform, as the enlargement rates for all paths in the network will be essentially compatible and constant. The above consideration, which applies not only to gypsum, explains why maze cave patterns are such a common product of artesian speleogenesis. The last stage of artesian speleogenesis is terminated by localized breaching of hydrogeological confinement (such as along tectonic faults or by incising valleys), marked by a drastic increase of flow through the system. Flow will accelerate locally, causing increased enlargement rates along certain flow routes or zones, but this does not modify the already configured cave pattern significantly.

Major discrete tectonic fissures intersecting the whole gypsum bed represent a different development scheme (Fig.3-B). Their initial resistivity to flow is potentially low, if their width is large, so conduits grow fairly rapidly as breakthrough conditions might be present from the very begin-

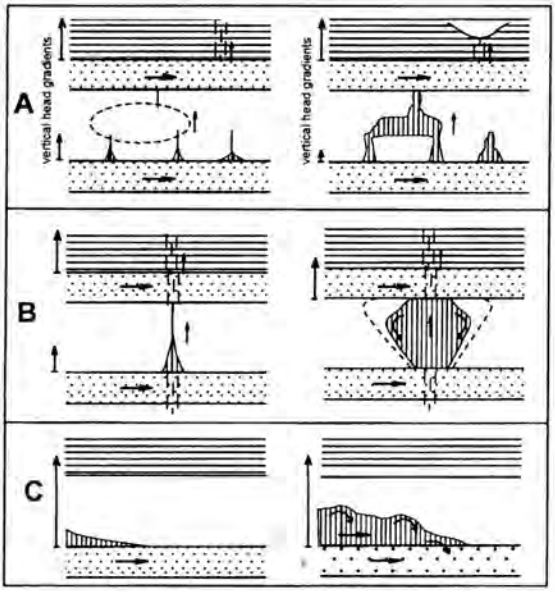

Fig. 3. Initiation (left) and development (right) of conduits and voids under artesian conditions. A = along common fissures; B = along a major tectonic fault; C = along a contact with an adjacent aquifer.

ning. However, enlargement rates do not accelerate significantly, as further increase of flow velocity is inhibited by the reduction in the head gradient between the upper and lower aquifers. As soon as an appreciable through space is created, much of the flow can reach the top of the gypsum without touching the gypsum walls. Under generally slow flow conditions, downward convection circulation cells develop, giving rise to an "inverted tapering" of the conduit shape (see more about the natural convection effect in the sub-chapter below). With further growth of through voids the head gradient between the adjacent aquifers tends towards zero, and circulation is driven largely by natural convection. This mechanism appears to be responsible for the continuing lateral growth of large voids in gypsum, and for triggering major breakdowns and the formation of vertical through structures (VTS) in coverbeds (see Chapter I.10 for details).

Dissolution also occurs along the contacts with the adjacent aquifers. In general, conduits initiate as tapers at inputs (Fig.3-C), however the actual mechanisms and shapes of the initiation and development depend also on the nature of the initial flow paths. These may follow bedding plane paths between solid rocks, be along the interface between solid gypsum and granular or porous aquifer material, or along water-conducting fissures in contact with the solid gypsum, and so on. Consequently, dissolved gypsum can be removed down-gradient along a bedding-related flow path, or in a direction normal to the lithological interface by diffusion or convection, then outflowing with the regional flow. The latter situation is most favourable for conduit initiation and development, as concentrations decrease at the interface, hence increasing the overall gypsum dissolution rate. Flow paths are guided by the arrangement of connected initial apertures along bedding planes, or by channels determined by intersections of fissures in adjacent insoluble rock with the bedding contact, or by more transmissive zones in adjacent granular material. When an aquifer underlies the gypsum, and some tapered space is created, further enlargement can be promoted by natural convection circulation. It is likely that some large voids can develop in this way.

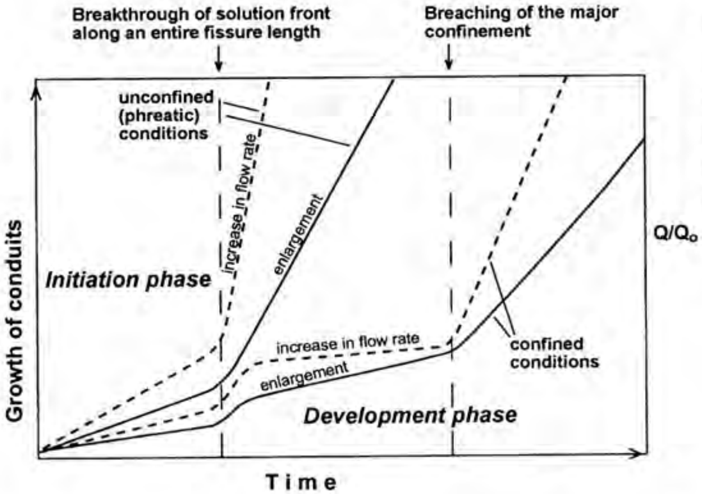

Fig. 4. Schematic diagram illustrating the dynamics of conduit growth through the initiation and development phases under phreatic and confined conditions.

5.3. Development at the water table and in the vadose zone

With the onset of the entrenched karst stage, vadose conditions become increasingly predominant, with the continued possible existence of water table and phreatic zones in the lower parts of massifs. Rapid enlargement of artesian and/or phreatic conduits occurs at the water table, particularly if annual fluctuations of major surface river levels cause periodic backflooding into a cave. In more stable conditions, such as in the interiors of watershed massifs, extensive horizontal notching may develop, promoted by water density stratification (see the sub-chapter below). In the vadose zone, cave development is concentrated along vertical percolation paths and free stream courses, but is very active locally. Hydrochemical data from different regions suggest that groundwaters in the vadose zone never attain saturation with respect to gypsum. More dispersed dissolutional enlargement may occur due to the action of condensation waters, but this effect tends to be localized in certain zones (see sub-chapter 5.4).

5.4. Speleogenetic effects of water density differences

Because dissolution always leads to solvent density increase, gravitational separation of water, and natural convection due to this effect, are inherently involved in, and affect, the cave development process. The effect may be significant in limestones (Curl, 1966) although is much more pronounced in gypsum (Kempe, 1972, 1975) and in salts (Frumkin, 1994) due to the higher solubility of these rocks. A recent overview and further elaboration of the issue has been provided by Klimchouk (1997b).

Water density difference effects generally become notable at the development stage, when substantial spaces are created by forced convection dissolution. In artesian settings the effects may also contribute to conduit initiation. When continuous or periodic recharge of fresh water occurs, dissolution of the rock sets up density gradients, which cause gravitational separation

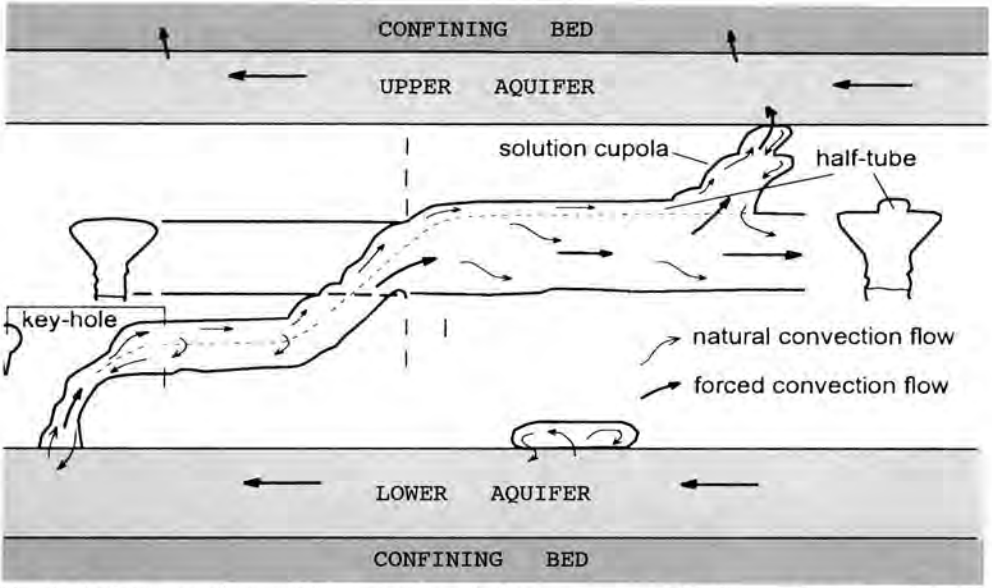

Fig. 5. The formation of upward dissolution forms by buoyant currents. The diagram shows the schematic relationship between lines of natural and forced convection flow on the mature stage of artesian speleogenesis, when conduit connection has already been established through the gypsum, but forced flow is slow due to the major constraint of the upper confining bed.

(stratification) of water and drive natural convection circulation. The phenomenon may operate at the local scale (e.g. in a cave lake) or at the scale of an aquifer (e.g. in artesian aquifers or across the water table zone).

Natural convection circulation and its speleogenetic effect are most pronounced in artesian settings because of sluggish flow conditions and low velocities, and also due to the commonly occurring recharge of gypsum from below. When sharp tapers are created at a fissure input at the base of a gypsum bed, dissolution is further promoted by natural convection circulation. After dissolving gypsum and increasing in density, part of the water returns downwards into the underlying aquifer and joins the regional flow output. It is quite possible that, under these conditions, dissolution driven by natural convection contributes even more to the upward propagation of enlargement through the fissure than does the penetration distance mechanism, driven by forced seepage, considered in sub-chapter 5.1. This view is supported by the common occurrence in many artesian caves of blind cupolas and domepits up to 10-15m high, with very tight fissures recognizable at their apices. In this way, vertical hydraulic connectivity between fissures arranged at different levels within a gypsum sequence is promoted, such that the effect facilitates the build-up of 3-D cave patterns. In more developed systems, where connection with the upper aquifer is established, directed (unlooped) buoyant currents operate, as less dense water always tends to occupy the uppermost available space. This is suggested (Klimchouk, 1997b) to account for the formation of at least some keyhole sections and ceiling half-tubes under artesian conditions (Fig. 5). In the case of large spa-

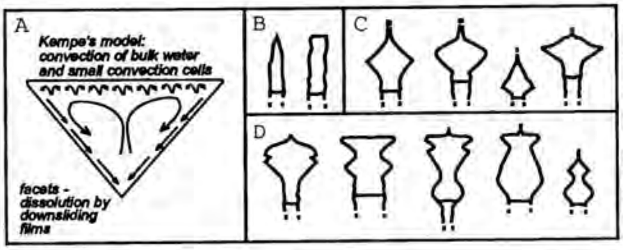

Fig. 6. Kempe's (1972) model of passage development by dissolution due to natural convection (A), and examples of typical cross-sections from the gypsum caves of the Western Ukraine showing varieties of notching or facetting effects.

ces that provide direct hydraulic connections between adjacent aquifers, downward convection is probably the main mechanism of lateral wall retreat (see Fig. 3-B and the sub-chapter above). Also, natural convection due to density differences is important to the development of cavities along the contacts between gypsum and underlying aquifers (Fig. 3-C).

Under shallow phreatic conditions, characteristic tip-down triangle cross-sections develop, with flat ceilings ("Laugdecke" in German), combined with inclined facets. They are quite common in many gypsum caves in Germany, the Western Ukraine, the Urals, Siberia and elsewhere, and have been studied in details and modelled theoretically by Kempe (1972) and Kempe et al. (1975). They are formed by dissolution in the uppermost, aggressive, layer of water, where patterns of small up- and downwelling convection cells ("salt-fingers") operate due to small local density differences (Fig. 6-A). Inclined facets are formed due to conduit-scale convection circulation, where films of water slide downwards along the walls, with progressive decrease in dissolutional potential.

Horizontal notching caused by chemical stratification of water, with the highest dissolution rates in the uppermost layer, may be a common morphological effect in caves within all major karstifiable lithologies (Ford & Williams, 1989).,It is, however, best displayed in salts (Frumkin, 1994) and gypsum (Klimchouk & Aksem, 1988; Klimchouk, 1997b; see also Fig. 6-C, 6-D).

5.4. Speleogenetic effects of condensation dissolution

In the aerated zone of well-karstified entrenched or exposed karst massifs, condensation processes can make a significant contribution to groundwater recharge. The role of condensation in karst hydrogeology and speleogenesis has been well studied in the Soviet Union, where Lukin (1962, 1969), Dubljansky (1970) and Dubljansky & Sotzkova (1982) elaborated theoretical issues and provided assessments and reviews of available field data, including some from gypsum karst areas. Cigna & Forti (1986), Forti (1991, 1993) and Calaforra et al. (1992, 1993) addressed the issue with particular regard to gypsum caves, but they were unaware of previous Soviet studies.

The amount of condensation water that can be formed in caves and fissures depends upon climate, the intensity of air exchange and temperature differences between the outside and in-cave atmospheres. It is most pronounced during warm seasons, under temperate climatic conditions and, especially, in the semi-arid zone. Water that condenses in transitional micro-climatic zones in caves is very aggressive, and causes substantial dissolution. The role of condensation corrosion in cave development is more important in gypsum than in carbonates, due to gypsum's high solubility and fast dissolution kinetics.

Lukin (1969) estimated that every cubic metre of air leaves 10g of water condensed on rock surfaces while passing throughout Kungurskaya Cave (in the Pre-Urals) during the warm season. Calaforra et al. (1993) suggested that, in the Cueva del Agua area of the semi-arid karst of Sorbas, all of the perennial base flow (about 1 L/s comprising 25% of the total discharge of the aquifer) was provided by condensation processes active inside the cave. Forti (1993) estimated that condensation accounts for more than 60% of the recharge of the karst aquifer associated with the Cueva del Leon in Argentina. Estimations by Dubljansky for different regions gave seasonal (the warm season) rates of condensation generated flow that vary from 1.4 to 9.7 L s^{-1} km^{-2}, comprising from 5.9 to 85% of the total recharge (precipitation minus evapo-transpiration). Klimchouk et al. (1988) approximated the rates of gypsum dissolution caused by condensation in the local zone inside the Optimisticheskaja Cave in the Western Ukraine to vary from -0.001 to -0.005 mg cm^{-2} day-1 according to season, with actual values reaching up to -0.02 mg cm $^{-2}$ day $^{-1}$ during certain 1-2 month periods. Thus, dissolution due to condensation can be a notably active agent of cave development.

6. Types of caves in gypsum karst

The above consideration of cave origin and development in gypsum provides a guide to the genetic classification of gypsum caves presented in Table 2. Below, the main cave types are briefly characterized, with reference to representative examples.

6.1. Discrete voids

Caves of this type develop commonly under artesian conditions, where the gypsum is underlain by an aquifer, and its own initial permeability is either very inhomogeneous, is determined by discrete major tectonic fissures, or is negligible. Their origin and development mechanisms are described in the section above (see also Chapter II.5). The best documented examples are caves in the Sangerhausen and Mansfeld districts of Germany, encountered through the centuries in the course of mining operations at depths up to 400m at the base of the Zechstein gypsum (Kempe, this volume). They are large voids, commonly isometric, or elongated along the major tectonic fissures like the Wimmelburger Schlotten (see Figs. 2-D and 4 in Chapter II.5). About 100 cavities of this type are known in the region. Natural convection circulation, driven by water density gradients, with dissolved gypsum flowing out with the regional flow in the underlying aquifer, is believed to play an important role in the development of such cavities (Kempe, this volume).

Breakdown of large voids formed in such a way is probably the main trigger of the development of vertical through structures (VTS). The latter is the generic term suggested for features including breccia pipes, collapse columns, and so on, common in deep-seated intrastratal karsts (see Chapter I.9 for details).

6.2. Maze caves

Maze caves constitute about 21% of the 197 largest recorded gypsum caves in the world, but their proportion increases to 41% among caves over 1000m long, and to 54% of gypsum caves over 2000m long. Considering the length of surveyed passages rather than the number of caves, just the five greatest mazes of the Western Ukraine comprise far more then half of all known gypsum passages in the world.

Palmer (1975) distinguished two major situations favourable for maze cave development: (1) where dispersed, aggressive recharge takes place uniformly into all available fissures in a soluble rock unit, entering from an overlying insoluble but permeable formation, and (2) where floodwater recharge causes temporal variations in discharge and head in an evolving system to be so great that no fixed passage configuration is allowed to stabilize with respect to flow (stream caves). Klimchouk (1992, 1994) suggested a third type of a genetic environment that favours maze cave development: upward recharge into a karst unit from the basal aquifer in a multi-storey artesian system. No unambiguous example of a cave in gypsum that could fit the first of Palmer's types is known to the present author, although this setting probably could produce mazes in gypsum. The second environment does not produce maze caves in gypsum as, due to the high gypsum solubility and fast solution kinetics, stream caves rapidly adjust their sizes to the highest possible discharge, so that no constrained floods occur. It appears that the great majority of maze caves in gypsum belong to the type of artesian mazes. The relevant hydrogeological settings are discussed in the Klimchouk' works cited above and in Chapter I.6; the theoretical substantiation of the origin and development mechanisms is outlined in section 5.2.

For typical rectilinear maze caves to develop, not only the artesian flow architecture favouring cross-formational upward hydraulic communication is required, but also a fairly uniform, though not necessarily high, initial fissure permeability within a gypsum bed. Otherwise discrete voids will tend to form rather than maze caves.

Artesian maze caves commonly display a multi-storey structure. Storeys are not related to cycles of stability/uplift (base level control) but are controlled stratigraphically: they develop at the lower and upper contacts of the gypsum, and inside the gypsum, within some intervals (beds) where initial fissures form networks that are well connected laterally but not well connected vertically. It is particularly common for lithogenetic fissures to form largely independent networks confined within certain horizons, with only local connections to adjacent fissured horizons (Klimchouk et al., 1995; see also Chapter I.1).

The most outstanding examples of mazes in gypsum are the great caves of the Western Ukraine (see Chapter II.9 for characteristics and maps). They are also known in the Belomorsko-Kulojsky, Povolzhje, Pre-Urals and some Siberian regions of Russia, in Germany and in Spain. Caves of this type are undoubtedly very common in many other regions of intrastratal karsts, but favourable conditions are required for them to survive uplift and denudation to become accessible and be explored.

6.3. Through caves

Within exposed gypsum karsts, or intrastratal entrenched karsts, the most common caves developed in adjustment with the given geomorphic configuration (not inherited from the previous stages) are linear or crudely dendritic caves that directly connect sink points and resurgence

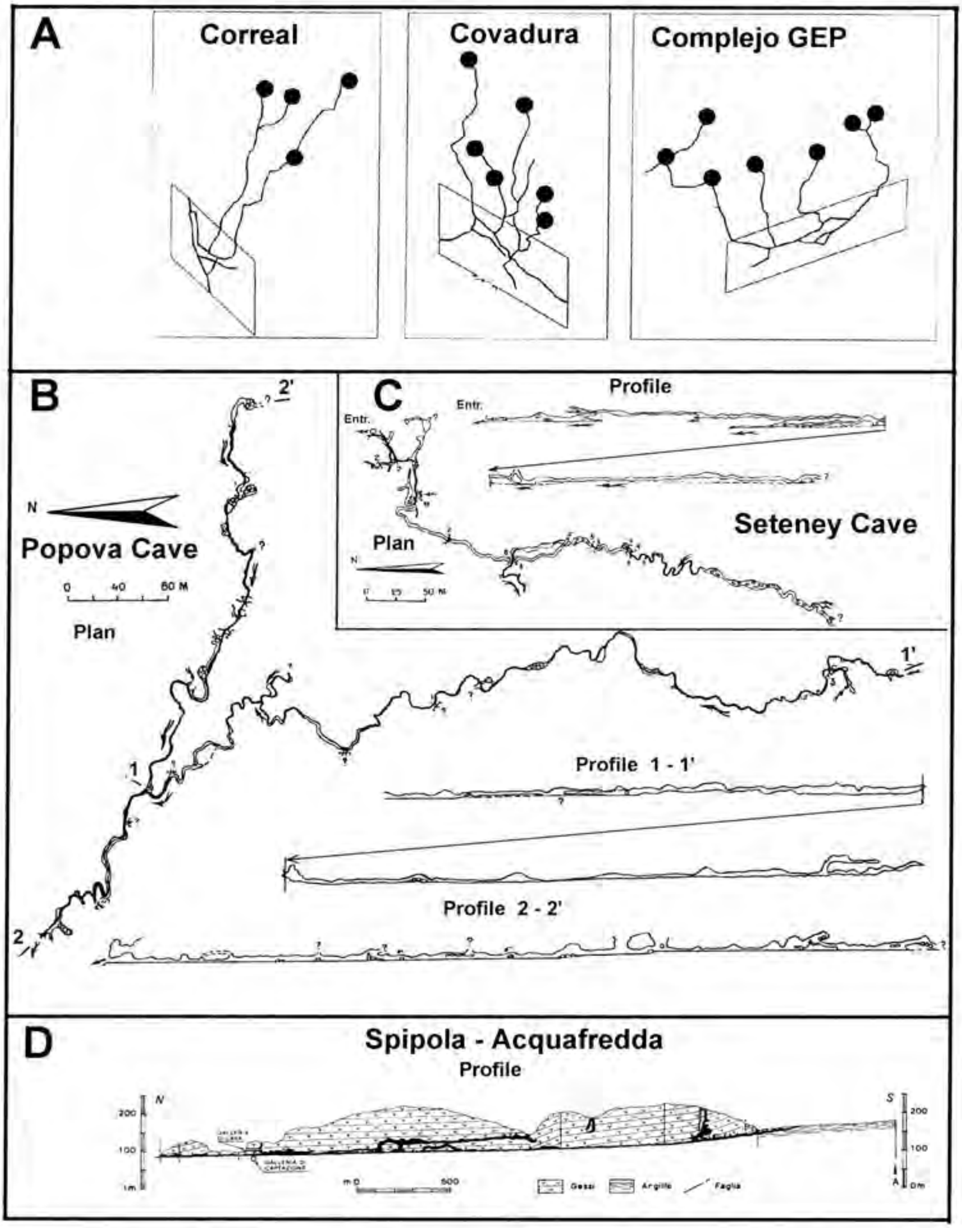

Fig. 7. Generalised sketches, plans and profiles of some gypsum "through caves": A = in Sorbas, Spain. Feeding dolines are indicated by dots. (After Calaforra, 1996); B and C = in the Ekeptze-Gadyk massif, North Caucasus, Russia (after Ostapenko, 1994); D = the Spipola-Acquafredda system in the Emilia Romagna, Italy (After Grimandi, 1987).

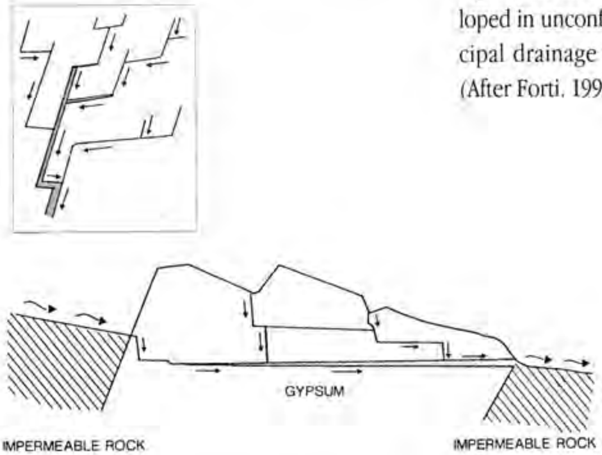

Fig. 8. Sketch of a typical gypsum karst system developed in unconfined conditions, consisting of a principal drainage tube with few and short effluents (After Forti, 1993).

points. They are collectively termed "through caves" in this account. As is shown in section 5.2, the "run-away" development and competition of alternative flow paths in unconfined conditions is exaggerated in gypsum, so that normally only one passage develops between input and output points (Fig. 7). When there are multiple sink points, a dendritic pattern may develop, as minor flow paths will ultimately connect to the nearest major successful conduit that serves as a drain (Fig. 8). Speleogenesis in gypsum under unconfined conditions creates extreme anisotropy of permeability, with rather simple and strongly hierarchical networks. Forti (1993) claimed the latter to be the principal characteristic of speleogenesis in gypsum, referring to confined speleogenetic environments as rare special cases. The actual situation can be said to be the direct opposite, considering that exposed or entrenched gypsum karsts, with no inherited caves at all, comprise only a minor part of the gypsum formations undergoing karstification (see also Chapter I.4).

Because of the fast development stage, "through caves" in gypsum adjust rapidly to the present base level. They also commonly develop along intercalated insoluble and poorly permeable (if compared with the now karstified gypsum) layers, or along the top of the basal formation, perched within the vadose zone. Perched streams "drop" into the nearest major tectonic fissure, forming vadose pits that connect different levels (Fig. 9). Intercalations in gypsum sequences play an important role in the early development of conduits under phreatic conditions. During the vadose stage, erosion of insoluble passage floors may become the predominant mechanism of their further development. This feature is well illustrated in the caves of Sorbas (Fig. 10).

"Through caves" are common in almost every entrenched and denuded gypsum karst area. The most representative and best documented examples are in the Emilia-Romagna and Sicily regions of Italy, the Belomorsko-Kulojsky, Pre-Urals and North Caucasus regions of Russia, at Sorbas in Spain, and in New Mexico and Oklahoma in the United States.

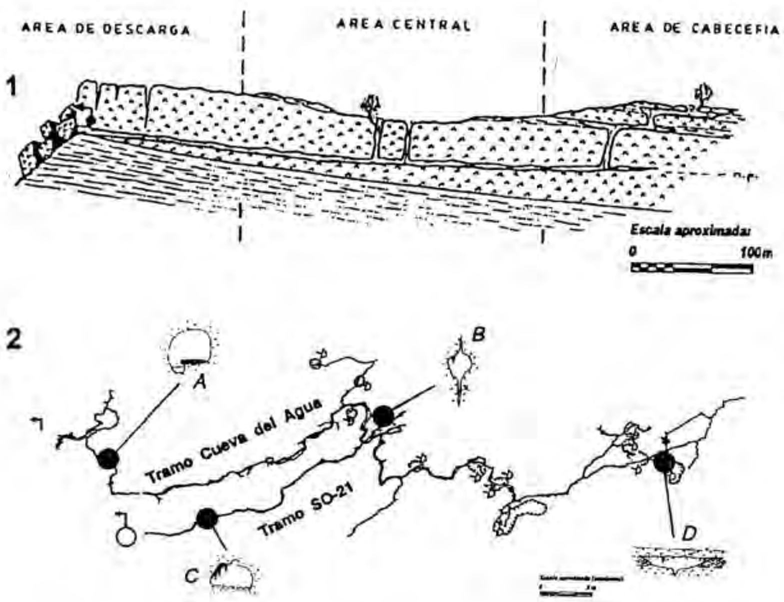

Fig. 9. Schematic profile (1) and plan (2) of the Cueva del Agua system, a typical "through cave" developed in the denuded exposed karst of Sorbas, Spain. Cross-sections of passages differentiate throughout the system: A = active passages in the downstream section, B = relict (abandoned) passages, C = phreatic passages with superimposed vadose canyons in the central section, D = vadose passages in the upstream section, where they developed by erosion of clastic intercalation layers (Adopted from Calaforra, 1996).

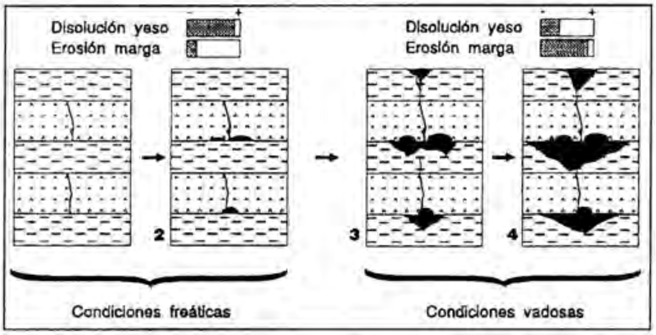

Fig. 10. Speleogenesis of interstratal passages in the gypsum karst of Sorbas, Spain. 1-2 = initiation and development of solutional conduits in phreatic conditions above the contact with marl intercalations, 3 - 4 = development of passages in vadose conditions by erosion of clastic intercalation layers (After Calaforra, 1996).

6.4. Vertical pipes

Vertical dissolution pipes, also known as organ pipes, or "komins" in the Russian literature, represent a very common feature of entrenched intrastratal karst. They develop downwards from a suitable protective bed at the top of the gypsum (commonly limestone or dolomite), due to focused dissolution by groundwater that percolates through the overburden, or leaks from perched aquifers above the gypsum (see Fig. 3 in Chapter I.10). Pipes cut across the whole gypsiferous stratum, or down to the water table, commonly intersecting relict lateral caves. Their density in a given area depends mainly upon the abundance of percolating trickles in the coverbeds, and can be very high in some places, perhaps up to several hundred per km2. Pipe diameter depends upon the amount of percolating water. New pipes develop quite rapidly, reaching a diameter of 1 to 3m, before their growth rate slows down. Rapid growth of new pipes is evidenced by an example 1m in diameter in Zolushka Cave in the Western Ukraine, which developed during 35 years after a borehole drilled from the surface caused a new leakage point from the perched aquifer above through the intervening clay. Dissolution pipes commonly induce breakdowns and vertical through structures (VTS) in coverbeds (see Chapter 1.10). They also provide foci for doline development where coverbeds are scoured by denudation.

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Chapter I.6

HYDROGEOLOGY OF GYPSUM FORMATIONS

Alexander Klimchouk

Introduction

The hydrogeology of any karst aquifer is largely a function of the general hydro-stratigraphical/recharge-discharge configuration (boundary conditions) and of the structure of secondary karstic porosity. Both of these should be considered as being variable in time, in a response to changing geomorphic conditions and the "internal" development of a karst system. Hence, the evolutionary setting is one key to reaching an understanding of karst hydrogeology. This is particularly true for gypsum karst, because its development is normally more rapid than that of carbonate karst. Any generalization of the properties and behaviour of gypsum karst aquifers can be achieved only on the basis of an evolutionary approach.

Gypsum karst hydrogeology is described in several regional publications. Colombetti & Fazzini (1988) and Forti & Francavilla (1993) examined the Emilia-Romagna region of Italy; Pulido-Bosch & Calafora (1993) considered the Sorbas area of Spain; Johnson (1985, 1990) discussed Oklahoma in the USA; and many tens of works have appeared that relate to parts of Russia and the Ukraine. Gorbunova (1979) provided an important general overview of gypsum karst hydrogeology, and Forti (1993) attempted to derive some general principles. However, the latter appear to be applicable only to areas of barren exposed karst type.

General details of the evolution of gypsum karst and descriptions of its main types are outlined in Chapter I.4. It is shown that karst development normally begins in deep-seated intrastratal situations, under confined flow conditions, and continues through a succession of karst types referred to as: subjacent intrastratal, entrenched intrastratal and denuded exposed (originally intrastratal). This evolutionary trend progresses mainly as a response to tectonic movements and geomorphic development.

Development of conduit permeability in gypsum is considered in Chapter I.5. The important distinction, in terms of resultant permeability structures, is stressed as being that between confined and vadose flow conditions (see Chapter I.5 for details). Depending upon the initial fissure pattern, confined conditions favour either the development of uniform maze conduit systems or isolated large voids. Phreatic and vadose conditions favour development of linear or crudely dendritic cave systems. In whatever case, once they are enlarged to a certain extent, flow paths in gypsum tend to adjust rapidly to being able to transmit the maximum available flow.

1. Deep-seated karst - confined conditions

Initial hydro-stratigraphical configurations in deep-seated intrastratal settings are determined by composition, structure and thicknesses of the gypsiferous and adjacent formations. The most important consideration is whether a gypsum sequence is immediately adjacent to aquifer or low-permeable beds either below and/or above. In the case of low-permeability beds no substantial groundwater circulation can affect the gypsum, so it can pass through the entire intrastratal stage without any significant development of secondary karst porosity. When exposed at the surface following uplift, such gypsum sequences undergo karst development that is in balance with the current geomorphic configuration; this leads to formation of the barren exposed karst type. Its hydrogeology is discussed below.

Due to their relatively low primary porosity gypsum sequences that lie between normal aquifers behave initially as aquifuges, which separate aquifers hydraulically before the onset of speleogenesis. The origin and development of conduits under such conditions are considered in Chapter 1.5. The principal hydrogeological role of karst (speleogenesis) in such conditions is that it guides the establishment of hydraulic communication between aquifers in a confined system (Klimchouk, 1997). During the process of speleogenetic development the gypsum loses its isolating function and becomes increasingly transmissive until, eventually, providing full hydraulic communication between adjacent aquifers, such that the whole system behaves as a single aquifer. However, different horizons within this type of composite aquifer may have different types of porosity. Whereas vertically adjacent insoluble horizons retain their granular or fissure porosities largely unchanged, in gypsum the newly developed conduit porosity strongly predominates. Also, the structure of the conduit permeability may vary greatly, according to the pre-existing fissure structure that guides the initial speleogenesis (see Chapter I.5). This structure can impose notable heterogeneity and anisotropy of hydraulic conductivities and transmissivities in such composite aquifers, and upon their complex behaviour in response to other impacts, such as groundwater abstraction.

A good example of a composite aquifer that became a single hydrogeological complex due to speleogenesis in gypsum is the Miocene aquifer in the artesian belt of the Western Ukrainian gypsum karst (Klimchouk, 1997). A lower aquifer bed (below the gypsum) is provided by a regionally extensive sandy-carbonate member. The upper aquifer consists of epigenetic limestone. Confinement of the composite system is due to a marly-clayey sequence. Large-scale opencast mining operations (for sulphur ores in the supra-gypsum bed, and clay from the overburden) were started, based on an assumption that the gypsum would behave as an aquifuge and that major inflow to quarries would be a function only of the specific storage in the upper aquifer. However, during exploitation of the deposits, a significant and increasing inflow occurred through the gypsum from the lower aquifer, causing severe difficulties in achieving the projected level of quarry floor lowering. The water withdrawal in some specific cases has reached levels of $1.2m^3/s$ (from the Jazovsky deposit) and $3.3m^3/s$ (from the Nilolaevsky deposit). Hydraulic communication between the lwer and upper aquifers is provided by well-developed conduit systems in the gypsum, analogous to the relict maze caves that are known in adjacent areas. Water tracing experiments have proved that lateral flow within the extensive drawdown cone occurs through all the members of the composite aquifer, with considerable mixing between them (Klimchouk, 1997).

Breakdown of large cavities in gypsum can trigger the development of vertical through structures that propagate upwards across overlying strata (see Chapter I.9 for details). Such structures commonly breach overlying poorly permeable beds, providing hydraulic communication with still higher aquifers. By this means the "communicative" hydrogeological role of gypsum karst described above can extend through the full vertical section of a basin.

Hydrogeological settings corresponding to deep-seated intrastratal karst are best represented in some parts of the United States (especially New Mexico), Germany, the Western Ukraine, Russia (pre-Urals) and China.

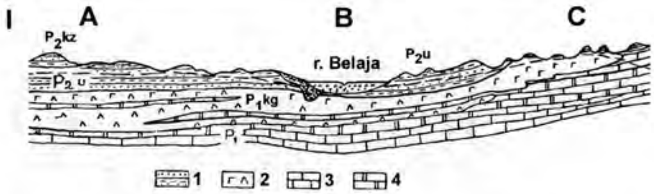
2. Subjacent, entrenched and denuded karst types - semi-confined, phreatic and vadose conditions

The stage of subjacent intrastratal karst is achieved when continuing uplift brings a gypsum sequence to a shallow enough position to allow partial breaching of artesian confinement by incising major valleys (Fig.1: I-B, II, III, IV, V-A). Inherited conduit permeability is further enhanced as flow through gypsum is intensified due to open upward discharge from the artesian aquifer system. At basinal scale, head gradient fields became more complex due to the increasing influence of surface topography. Permeability, transmissivity and storage characteristics are commonly high at aquifer scale, though they become even more inhomogeneous, due to local steepening of hydraulic gradients, focused discharge and dissolution. Recharge/discharge configurations become more diversified in such areas. A gypsum stratum can receive upward recharge from underlying aquifers (mainly within topographic lows - large valleys), recharge from above (mainly within topographic highs - inter-valley massifs), or recharge from the side (within the local outcrops of inclined beds or zones of lateral contact with other aquifer formations).

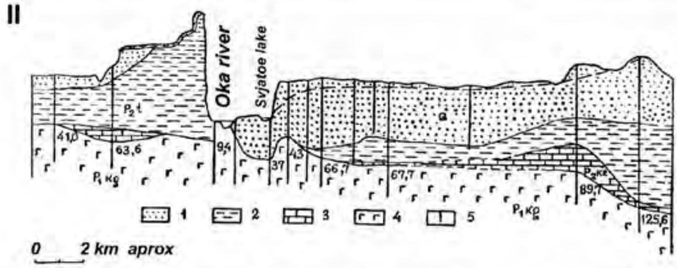
This type of karst is characterized by increasingly evolving point recharge through collapse dolines within inter-valley massifs, by widely occurring hidden discharge from gypsum aquifers into alluvial sediments and river beds, and by the presence of large ascending springs and karst lakes fed from below. Karst springs generally have quite steady discharges. commonly of the order of several hundred L/s, but locally more than $1 m^3/s$. The lateral flow component is increased towards major valleys and along them. Lateral flow through gypsum can be established locally between adjacent valleys that are incised into the same aquifer to different depths.

When erosional incision below the base of an upper confining bed becomes significant, a vadose zone and water table establish in the surrounding area (Fig. 1: II). This is already a transitional stage between subjacent and entrenched karst types. The latter is achieved when some major valleys have incised through the majority of, or through the full thickness of, a gypsum sequence. The water table commonly has a low gradient and may propagate deep beneath inter-valley massifs, as the permeability and transmissivity of gypsum aquifers are quite high due to the effects of the preceding karstification.

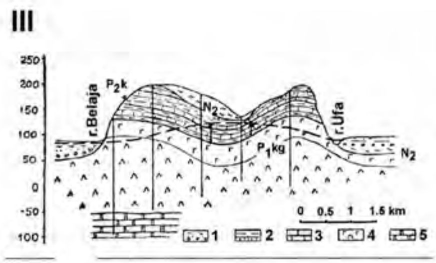
In some extensive gypsum karst regions that are characterized by a complicated block tectonic structure, lateral facies variation within sediments, varied depths of erosional incision and different rates of denudational stripping of cover beds through an area, lead to some mixed and complex hydrogeological settings being present (Fig. 1: I, V). Modes of recharge and discharge, and flow conditions for the same aquifer can change considerably across a single area. In areas of unconfined flow, downward point recharge predominates where low-permeable cover beds



Western flank of the Bashkirsky dome and the Birsky depression (After Hydrogeology of the USSR..., 1972). 1 = clay, sandstone and marl, 2 = gypsum and anhydrite, 3 = limestone, 4 = dolomite.



Dzerzhinsky city area in the Volga-Kamsky region (After Karst phenomena..., 1960). 1 = sand, 2 = clay, marl and shale, 3 = limestone, 4 = gypsum and anhydrite, 5 = boreholes. Numbers indicate the depth to the top of gypsum.

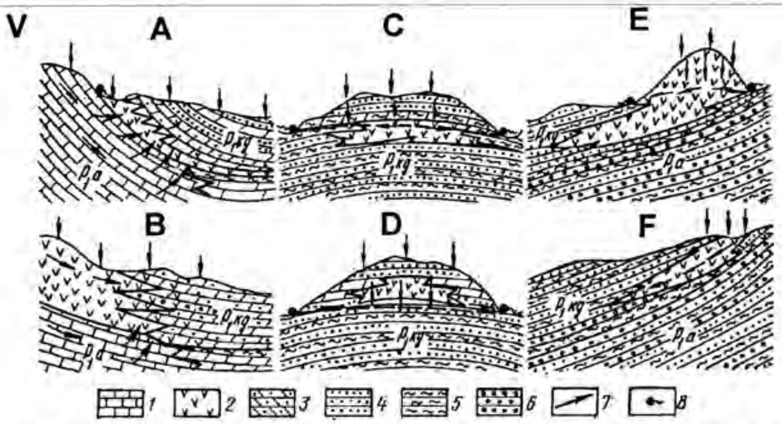


Ufimsky plateau (After Kudrjashov & Martin, 1970). 1 = alluvial deposits, 2 = clay, argillite, sandstone, 3 = limestone, 4 = gypsum and anhydrite, 5 = dolomite. Dashed line indicates potentiometric level of groundwaters.

Intervalley of Ater and Tjuy rivers, Perm region (After Shimanovsky, 1966).

Fig. 1. Geological and hydrogeological profiles of different areas of the pre-Urals karst region illustrating settings of intrastratal deep-seated (I-A, V-A, V-C), subjacent (I-B, II, III, IV, V-A), entrenched (V-D) and partially denuded (I-C,V-B, V-E) gypsum karst.

See also Fig. 1. V. in the following page.



Northern part of the Urjuzano-Sylvinsky depression (After Maximovich & Ikonnikov, 1979). A, B = western flank; C, D = central part; E, F = eastern flank. 1 = limestone, 2 = gypsum and anhydrite, 3 = marl, 4 = sandstone and shale, 5 = argillite, 6 = conglomerate, 7 = directions of underground water flow, 8 = springs.

remain, and dispersed downward recharge occurs where gypsum is exposed and the surface karst form density is high. Upward recharge can contribute simultaneously where the gypsum is underlain by aquifer formations. The region that best displays such a wide variety of hydrogeological conditions is the pre-Urals, in Russia, from where all of the component examples in Fig. 1 are derived.

Because high permeabilities and transmissivities are commonly inherited from previous stages, unconfined aquifers in these settings are well-integrated, with a low-gradient water table and low localization of lateral flow. Dissolution is now focused around recharge points and at the water table, and contributes to further void enlargement. However, this does not change the preexisting hydraulic conditions. Localized flow occurs only in entirely entrenched and drained situations, where free streams, perched on non-karstifiable interbeds, or on top of an underlying impermeable sequence, flow underground from sink points to resurgences. The Belomorsko-Kulojsky plateau, in northern Russia, is a representative example, with its numerous linear stream caves locally superimposed on dispersed networks of relict conduits.

3. The "pure" line of hydrogeological evolution of barren exposed gypsum karst

The barren karst type represents the case where gypsum is exposed at the surface without having experienced any substantial development of karstic porosity before exposure, or where a previously evolved karst porosity has been largely fossilized. Karstification then develops in balance with the contemporary (exposed) geomorphic setting. In Chapter I.5 it is shown that, due to the fast dissolution kinetics of gypsum, the "run-away" development and competition of alternative flow paths within gypsum under unconfined phreatic conditions is exaggerated, so that normally only one passage develops between input and output points. Thus, this type of speleogenesis in gypsum leads to an extreme heterogeneity and anisotropy of karst permeability, with relatively simple and strongly hierarchical networks (see Fig.8 in Chapter I.5). These relationships were outlined by Forti (1993), who stressed that drainage routes in gypsum rapidly adjust their dimensions to accommodate the maximum available recharge, and their positions to the current base level. The underground flow in gypsum under such conditions is commonly highly localized, in the form of free-running streams. Transmissivities are normally high in barren gypsum karst aquifers, and storage capacities are low. No substantial flow occurs at greater depths below the water table.

The typical characteristics of barren gypsum karsts are best exemplified by the gypsum karst areas of Sicily and Emilia-Romagna, in Italy, and of Sorbas in Spain. They also apply in areas of entrenched and denuded karst conditions where previously developed karstic porosity is highly heterogeneous and locally low. However, in the latter case, this style of karstic porosity may determine only local peculiarities rather than the hydrogeological properties of an entire aquifer.

Another peculiar characteristic of the karst types mentioned above is that, with a well-developed vadose zone and ventilated karst-fissure permeability, condensation recharge may contribute significantly to the total recharge of an aquifer, particularly in areas that suffer arid and semi-arid climatic conditions (Dubljansky, 1970; Forti, 1993; see Chapter I.5 for details).

4. Flow velocities in gypsum karst aquifers

Data on flow velocities in gypsum karst aquifers are scarce in comparison with the great amount of data available for carbonate karst.

Klimchouk & Aksem (unpublished) have carried out numerous tracing experiments to investigate flow in the confined composite aquifer in the vicinity of the Jazovsky sulphur deposits. The area represents a deep-seated karst setting, but large-scale opencast quarrying during the past 30 years has breached artesian confinement and imposed subjacent karst conditions. The flow system is centripetal, directed toward the main quarry, within an extensive drawdown cone induced by massive underground water withdrawal. Some 30 tracer injections have been performed via boreholes, with detection monitored via other boreholes. The maximum proven lateral distance of hydraulic connection was 16km. Tracers injected into the lower aquifer were commonly detected in gypsum, and vice versa, indicating close mixing of flow between these horizons. The apparent flow velocities, calculated for maximum tracing distances, vary between 700-1100m/day, while velocities calculated for successive distances between adjacent boreholes range from 400 to 2500m/day.

In the adjacent Podol'sky area entrenched karst conditions predominate. The water table lies within the lower part of the gypsum bed beneath the inter-valley massifs, and a saturated zone extends down into underlying sandy-carbonate sediments, perched on low-permeability Cretaceous beds. Tracing experiments in the area of the Ozernaya maze cave, with tracers injected via ponors and intercepted at springs along the valleys, have revealed a wide distribution of tracers through the area and apparent flow velocities ranging from 300 to 500m/day.

The highest flow velocities are recorded in barren exposed karsts, where water movement is localized in the form of through-flowing underground streams. Forti (1993) referred to tracing experiments performed in the gypsum karsts of Sorbas (Spain) and Emilia-Romagna (Italy), which shown apparent flow rates ranging from 8.64 to 129.6km/day.

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Chapter I.7

SPELEOTHEMS AND CAVE MINERALS IN GYPSUM CAVES

Paolo Forti

Abstract

For many years gypsum karst was considered to contain little of interest from the point of view of chemical deposits. Relatively recently a general study of speleothems has begun within gypsum karst areas in different climatic zones around the world. So far this ongoing research has shown that gypsum karst can be very interesting in terms of its contained chemical deposits. In this chapter, all that is currently known about speleothems in gypsum caves is reported systematically, and the distinctive climatic control over them is emphasised.

1. Introduction

Gypsum karst has long been thought of as a second-class phenomenon, far less interesting than limestone karst from the point of view of the speleothems that it contains. Only since the nineteen-eighties have cavers and scientists realized that gypsum karst may develop unusual epigean and hypogean forms and chemical deposits, which are commonly just as interesting as those in limestone. Speleothems are generally uncommon in gypsum caves and therefore papers discussing the genesis of chemical deposits in these caves are rare. Recently a widespread study has begun on gypsum karsts in different climatic zones around the world. This research is still in progress but has so far shown that gypsum karst can differ significantly from limestone karst with respect to its speleothems, and particularly that several unusual chemical deposits are developed locally within it.

Until now, however, very few studies have been made on chemical deposits (speleothems and secondary mineralization) in the world's gypsum caves, and most of the few detailed studies have concerned Messinian and Triassic gypsum sequences in Emilia Romagna, Italy. Some specific research has recently been undertaken in other parts of the world (including Spain, the United States, the former Soviet Union, Cuba and Argentina), though as yet the distribution of this research coverage is patchy, or it is only partially complete. This chapter reviews all that is known about speleothems (calcite and gypsum), with particular reference to those forms that are found exclusively in the gypsum environment. An updated list of secondary cave minerals is also provided and, finally, the fundamental role exerted by climate in controlling all secondary chemical deposits in gypsum caves is discussed.

2. Speleothems

Speleothems in gypsum caves exist essentially as calcite and gypsum deposits; these two categories are considered separately.

2.1. Calcite speleothems

Calcite speleothems are reasonably widespread in gypsum karst areas, though limited areally by climatic conditions. Their maximum development occurs in areas of temperate continental climate (like Emilia Romagna, Italy), or in pluvial tropical zones (such as in Cuba). Stalactites, flowstone, splash concretions and cave pearls are the most common forms, and they show no morphological peculiarities to distinguish them from similar, but far more common, deposits in limestone caves (Maksimovich, 1969, 1972). It should be noted though, that in most cases their depositional mechanism is unlike that which dominates in the limestone environment (supersaturation caused by diffusion of carbon dioxide into the cave atmosphere). In fact, calcite speleothems have commonly been noted in gypsum successions where there are no superimposed calcareous strata. Thus, the most usual origin of calcite speleothems in the gypsum karst environment cannot be dependent upon re-deposition of calcite that was dissolved earlier by seeping rainwater. Not until the early nineteen-eighties (Forti & Rabbi, 1981) was it demonstrated that calcium carbonate deposition in such cases is controlled by the presence of carbon dioxide dissolved in infiltration water. The formation of calcite speleothems in gypsum caves is no more than a product of the incongruent dissolution of gypsum by water with a high initial carbon dioxide content. A distinctive characteristic of calcite speleothems formed by this mechanism is that they are almost inevitably found a few metres, or a little more, from the point where the water inlet enters the void in the gypsum rock.

Incongruent dissolution explains not only the origin of normal speleothems in many gypsum caves, but also the existence of unique forms (observed only in this environment) comprising crusts detached almost completely from highly corroded gypsum walls. The same mechanism is also responsible for the development of large (14m high, 2m wide and typically less than 20cm thick) "calcite blades" with mud nuclei (see Fig.1) that are present in some Italian and Cuban caves (Forti & Rabbi, 1981; Forti, 1991, 1992).

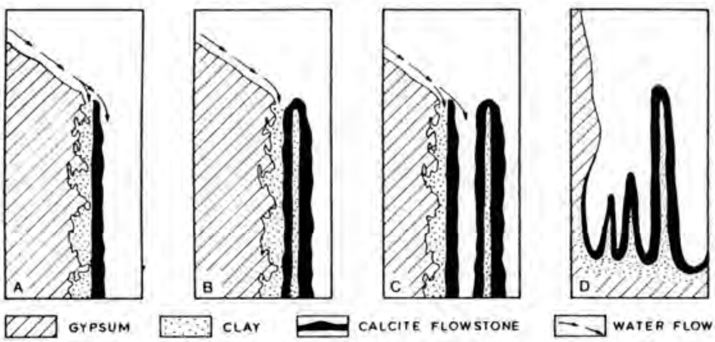

Fig. 1. The origin of "bladed flowstones": A) flowing water dissolves gypsum wall rock and leaves insoluble clay residue behind while simultaneously depositing calcite flowstone over the clay; B) the flowstone protects the underlying clay and mud, thin "bladed flowstone" is produced; C) the process is repeated again, and so forth, until a series of thin blades is left, arranged parallel to the wall (D) (After Hill and Forti, 1986).

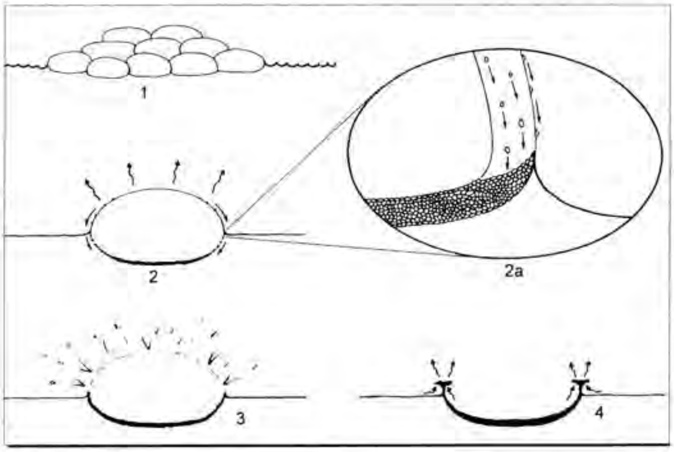

Fig.2. Diagram showing the development of half bubbles and calcified foam in Grave Grubbo Cave, Italy: (1) development of foam over the pool surface; (2) development of small calcite rafts along the upper part of each foam bubble(s) induced by CO_2 diffusion and evaporation, and consolidation of the lower part of the foam bubble(s) by the gravity sinking of small rafts developing in the upper part of the water film of the foam bubble (2a); (3) breaking and floating of the half bubbles; and (4) enlargement of the border of the half bubbles by capillary uplift and evaporation (After Forti and Chiesi, 1995, modified).

The strangest calcite speleothem type, which occurs only in the gypsum environment, has been reported from a single cave (the Grave Grubbo, Calabria, Italy), where an unusual type of cave bubble (half bubble) has been found (Forti & Chiesi, 1995). These speleothems develop due to a peculiar form of incongruent dissolution. Carbon dioxide is supplied by the progressive oxidation of suspended organic matter in an underground, sulphide-rich, river. These unique speleothems consist of multiple calcite half-bubbles, from 0.2 to 1-1.2cm in diameter, cemented to each other and floating on a pool surface (see Fig.2). The "half-bubbles" were deposited due to the oxidation of organic matter in an environment that is saturated with gypsum. Oxidation of organic matter in the cave water causes evolution of a long-lasting foam floating on the pool surface and simultaneously supplies a large amount of carbon dioxide. This reacts with Ca^{2+} ions in the foam's gypsum water film, forming calcite micro-crystals. These in turn become cemented within the lower part of the bubbles. This process goes on until the bubbles eventually explode, causing "calcite half bubbles" to form.

While considering how rapidly calcite speleothems develop in a gypsum environment , it was observed that, contrary to what might be supposed, the development velocity is commonly higher than that of similar forms in limestone caves. Experimental observations have demonstrated a growth rate of almost 1mm/year for some flowstones (Dal Monte & Forti, 1995). Faster growth rates of calcite speleothems in gypsum environments relative to those in limestone are clearly associated with the exceptional efficiency of the incongruent dissolution process.(Forti, 1991, 1992).

Lastly, it has been noted that there is a difference between what happens in limestone caves and gypsum caves with regard to the formation of structural bands within calcite speleothems. In gypsum caves, rather than speleothems displaying an annual cyclicity, a much higher frequency of banding is typically present (Cazzoli, 1988). The explanation of this is again related to the incongruent dissolutional mechanism, which is active only in the first few metres of percolation inside the gypsum. Close to the surface impulses caused by individual rainfall events are still important, and frequent hiatuses in the water supply potentially lead to the evolution of a new growth layer with each stop and start in the precipitation

2.2. Gypsum speleothems

Despite the aspects discussed above, it is the gypsum speleothems and crystal forms that hold the strongest elements of interest, as well as having a more ubiquitous distribution. Gypsum speleothems present obvious morphological differences compared to calcite ones, due to their distinct genetic mechanism, which involves supersaturation due to evaporation. Gypsum stalactites are typically more contorted, spotted and multi-branched. In most cases their growth depends much more, if not exclusively, upon surficial percolation water rather than upon water that feeds through a central tube. This commonly results in the central tube being absent, or partially (if not completely) obstructed.

The effect of permanent air currents (or at least those that are active during the stalactites growth periods) is the exact opposite with respect to calcite and gypsum stalactites. In fact, in the case of the former, as the growth mechanism is controlled by carbon dioxide diffusion, which is not influenced in any way by the air current, there is commonly a deviation of the stalactite in the direction of air movement, which is the same direction that the water droplets are deviated before they fall. In the case of gypsum stalactites, the inverse effect dominates, as the speleothems deviate towards the source of the air current, where maximum evaporation occurs.

In the hot and dry zones of New Mexico a still more complex evolution of deflected gypsum stalactites is observed. This phenomenon takes the form of stalactites shaped like an "elephant's foot", presenting a notable swelling that is commonly inclined downwards close to the top (Calaforra & Forti, 1994; Chiesi & Forti, 1996). These gypsum stalactites owe their genesis to a combination of factors that are rarely found together at a single locality. In fact, these speleothems form only when they are situated in a constant air current, and are fed by slightly undersaturated water (condensation water). Moreover, the temperature must be high enough to guarantee rapid evaporation, thus allowing saturation to be achieved at a well-marked level on the speleothem (the site of the swelling).

Stalactites are found quite commonly in Italian caves, but stalagmites are relatively rare. This "rarity" is basically a reflection of the climatic conditions, which allow the easier evolution of inflorescence so that capillary uplift and evaporation can take place. In areas of warmer, dryer climate (such as Sorbas, in Spain, and New Mexico) stalagmites are as common as stalactites (Calaforra et al, 1992).

The fact that evaporation, is the dominant genetic mechanism during the evolution of the

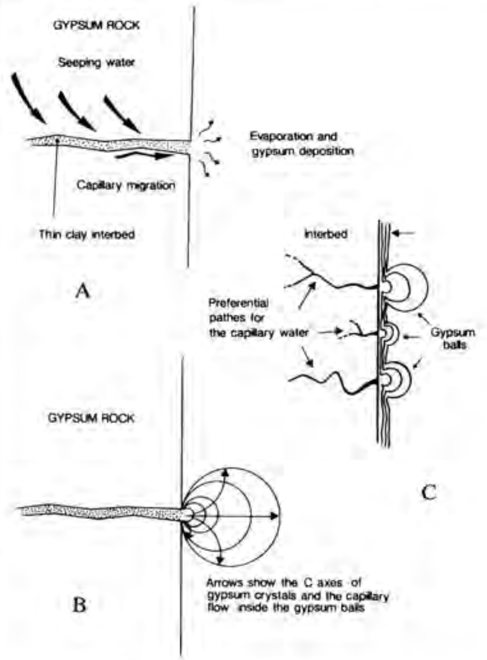

Fig. 3. Evolution sketch for the gypsum balls in the karst of Sorbas (Spain): A) the horizontal disposition of the gypsum strata with thin clay interbeds drives the capillary mouvements of the seeping water to the wall surface where evaporation occurs; B) the cross-section of the gypsum ball shows its spherical growth and the rotation of the c axis of the gypsum fibres to become perpendicular to the rising surface; C) cross-section parallel to the bedding plane showing the development of gypsum balls just in the places intersected by preferential capillary flows (After Calaforra and Forti, 1993).

gypsum deposits, explains why some types of speleothem, common in calcite, are very rare in gypsum, and vice versa. Compared to calcium carbonate, gypsum forms helictites with extreme difficulty. This is because, as already mentioned, evaporation leads to an even greater obstruction of the feeding capillaries than is normally characteristic of these speleothems in calcite. Small gypsum helictites have been found only in a single cave in Sicily (Italy), (Forti, 1987). In contrast, it is much easier for wind-related speleothems, such as rims and trays, to develop in this environment (Chiesi & Forti, 1992; Calaforra & Forti, 1994).

Gypsum caves also host unusual speleothems, like "gypsum balls" and "hollow stalagmites", both described from the Sorbas caves (Spain) (Calaforra & Forti, 1993; Calaforra, 1996). The balls (see Fig.3) are layered, spheroidal gypsum formations (up to 10cm in diameter) with an internal structure consisting of radially elongated crystals. They develop on the cave walls along sub-horizontal layers with thin limey, sandy interbeds, and are found exclusively in the deepest parts of the caves, where water flow and supersaturation remain constant. The sub-horizontal disposition of gypsum layers with thin clayey interbeds favours capillary drainage of supersaturated water towards preferred places in the cave walls, where evaporation and precipitation can proceed, allowing the evolution of the gypsum balls. Normally, the gypsum balls are compact and consist of lengthened gypsum fibres that assume a radial structure. As they mature, such speleothems may evolve an internal drainage tube inside a related clayey interbed. The consequent arrival of water, sometimes unsaturated, at the level of the balls can, in some cases, cause the emptying of the balls, and sometimes their complete destruction.

Hollow gypsum stalagmites (see Fig. 4) have been reported from a cave in the Sorbas area

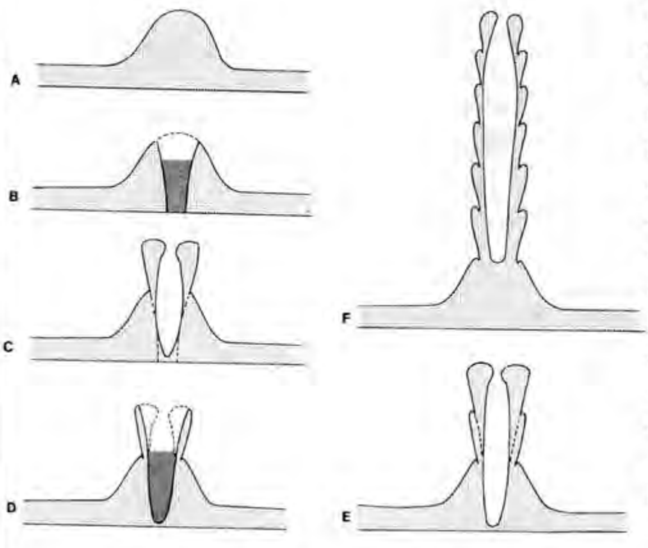

Fig.4. Steps in the evolution of gypsum hole stalagmites: A) development of a normal stalagmite due to oversaturated dripping during a semi-dry period; B) undersaturated leakage forms a hole in the stalagmite during a wet period; C) capillary uplift and evaporation in dry periods, showing the evolution of the first conical segment of the stalagmite; D) a new wet period refills the stalgmite with water and the subsequent dry period (E) causes the development of another conical segment; F) final shape of the hollow stalagmites (After Calaforra and Forti, 1993).

(Spain) and from a cave of New Mexico (Calaforra & Forti, 1993). They are very narrow and up to 150cm tall stalagmites, with an external diameter of no more of 4-6cm and an internal tube that is 2-3cm in diameter and commonly reaches the bottom of the stalagmite. In both known occurrences these speleothems were observed close to the land surface, where fresh seepage water can arrive very rapidly. The climate of both areas (hot and dry, with rare rainstorms) is fundamental to the development of hollow gypsum stalagmites. During short, intense wet periods, infiltration water reaches the cave passages undersaturated with respect to gypsum and is capable of "drilling", or at least keeping open, the central tube in the stalagmites. In dry periods (practically all of the year), capillary-evaporation processes related to the water stored inside the tubes of the stalagmites causes the growth of their tops.

Gypsum crystals, between several microns and more than a metre in length, are without doubt the most common secondary deposit found in caves at all latitudes and in all climatic zones. They are commonly found as free deposits, though more typically they form druses anchored to the cave walls. The smallest gypsum crystals (from 10-100 microns) are found widely in the form of "gypsum powder" deposits, which can develop due to several different mechanisms. They may cover the ice flows in Siberian caves (Forti, 1990,1991), deposited due to fractional crystallization during freezing. In the gypsum caves of New Mexico, they can cover the cave walls during brief periods in between rainstorms (Calaforra & Forti, 1994). In this situation the gypsum powder develops due to sudden evaporation of capillary water that reaches the cave walls just after a flood. Gypsum powder also forms over large deposits of guano in areas of temperate climate, and in such cases the deposits develop by the mineralization of guano in a strongly sulphate rich environment (Forti, 1989). Finally, gypsum powder can be a rehydration product of bassanite in tropi-

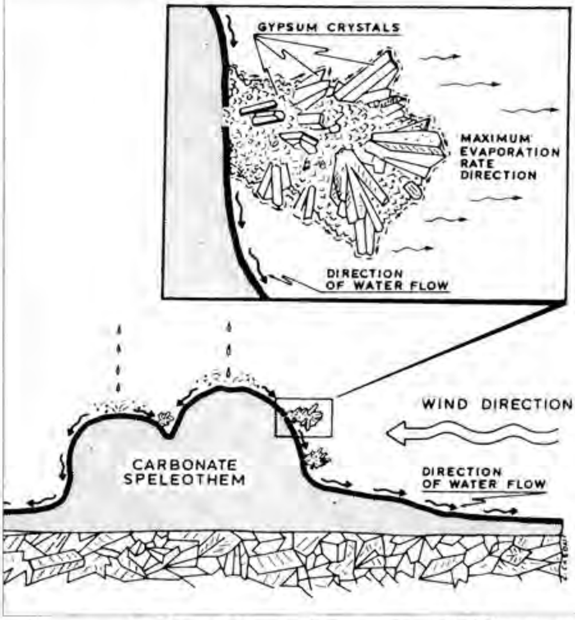

Fig. 5- Evolution of gypsum flowers over calcite speleothems in the gypsum caves of Bologna: water oversaturated with respect to calcite flowing over the wall and the floor of the caves deposit calcite flowstones. A part of the same water is driven by capillarity on top of the speleothem's roughness where it evaporates giving rise to gypsum flowers

cal areas, as has been observed in some small Cuban caves.

The largest crystals (some more than a metre long) form typically inside clayey sandy interbeds in the caves of temperate areas, where their development is driven by the slow flow of capillary waters, whose evaporation causes a very small level of supersaturation. It is not feasible to describe all the different varieties, types and forms of gypsum crystals here, as they display enormous variations with respect to shape, dimensions and purity. The genetic mechanisms can also vary significantly, even though at a simple level the genesis of these crystals can normally be viewed as the result of simple supersaturation following evaporation. Detailed discussions of these questions can be found in specific papers by Casali & Forti (1969), Forti et al. (1983), Hill & Forti (1986) and Forti (1988, 1989, 1990, 1991).

Gypsum flowers, which represent the genetic analogues of calcite coralloids, are practically ubiquitous, and owe their genesis to evaporation of a thin water film that is drawn slowly up wall discontinuities, driven by capillarity. Their evolution is relatively rapid and appears identical to that of the calcite or aragonite coralloids in limestone caves. The unique feature displayed by these gypsum outgrowths is that of being highly sensitive to air currents. In gypsum caves it is common to see such formations with gypsum macro-crystals elongated toward the wind direction. A classical case is provided by the wind controlled flowers that develop inside "gypsum chimneys", which are sub-vertical corrosion-condensation conduits that develop where there is a continuous strong, hot and humid air current flowing upwards, in the karst area of Neuquen in Argentina (Forti et al, 1993).

Another relatively unusual type of inflorescence, though more common in caves with a humid temperate or tropical climate, takes the form of the gypsum crystals growing over active calcite speleothems (Fig. 5). This occurs notwithstanding the fact that the gypsum precipitation mechanism is completely different to that of calcite in a gypsum cave. The calcite precipitates due to diffusion of carbon dioxide into the cave atmosphere, or following incongruent dissolution, whereas the gypsum is deposited as a result of supersaturation due to evaporation. (Forti & Marsigli, 1978)

3. Cave minerals

When considering the other secondary minerals that can be found inside gypsum caves, it must be remembered that up until the early nineteen-seventies only two minerals had been identified (Laghi, 1806; Bertolani & Rossi, 1972). This situation arose primarily because practically nobody was interested in this specific area of study. Also, there was a well-rooted opinion that if the world's gypsum caves were poor in concretions, they would also be completely devoid of secondary minerals. Specialized research in this field has only begun during the last 15-20 years, but even then only in a few areas. First among these is the Emilia Romagna region, followed by others in Italy, the United States and Argentina, Ukraina (Forti, 1986a,b; 1989; Turchinov 1993). Though the extent of this study is evidently limited it has shown that effectively the gypsum cave environment is not rich in minerals. This is logical, if it is realised that gypsum rock is a salt of a strong acid (sulphuric acid) and therefore shows much less tendency than does limestone to react with any mineralizing agents that are potentially present in the cave environment.

Notwithstanding the limited research activity, occurrences of more than 20 minerals with distinct characteristics (summarised in the table) have already been described (Cervellati et al, 1975; Forti & Querzè, 1978; Rogozhnikov 1984; Chiesi & Forti, 1985, 1986, 1988; Forti, 1993; Turchinov 1993; Carrozzini et al, 1996; Turchinov 1996). It is likely that new varieties of mineralization will be located in the near future. It must be noted here that about half of the minerals

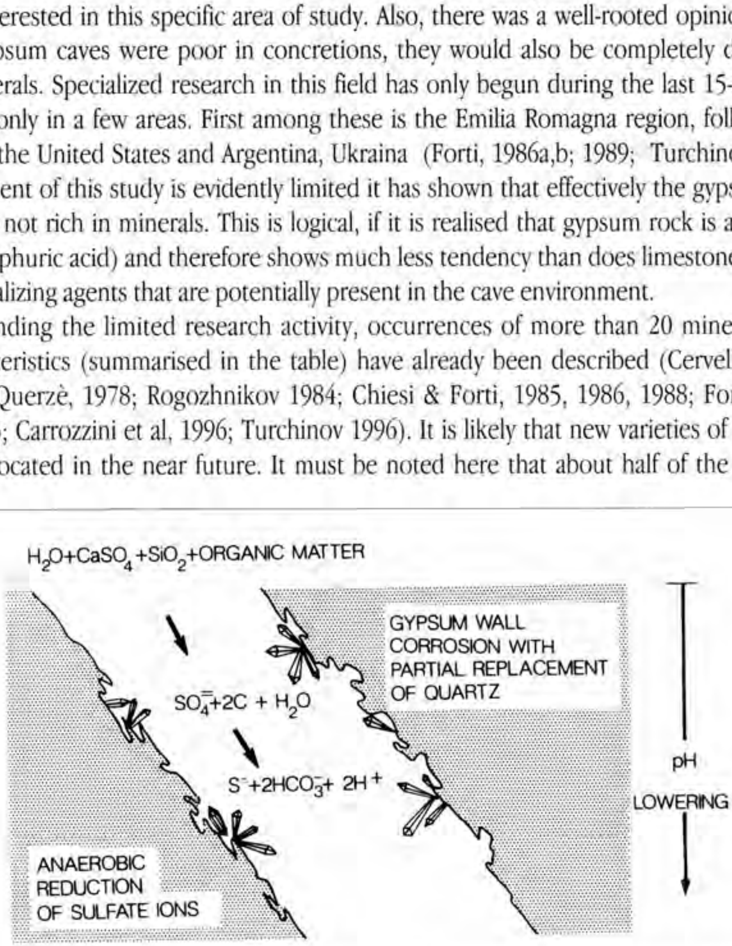

Fig.6- Sketch for the simultaneous dissolution of gypsum and deposition of skeletal quartz in the Monte Mauro caves (Italy): the anaerobic reduction of sulphates to sulphides with the oxidation of organic matter to CO2 lowers the pH, making possible the precipitation of silica and induces a slight undersaturation with respect to gypsum which is therefore dissolved (after Forti 1994)

already recorded have been found in caves where sulphide water is present or where processes connected to the sulphur redox cycle are active (Forti & Rossi, 1987, 1989; Forti, 1994).

A particularly important find was made in the cave of Vena del Gesso Romagnola (see Fig.6), where euhedral quartz crystals had developed upon corroded gypsum crystals, at normal temperature (Forti 1993, 1994). This find is highly significant, not only in the context of the karst environment in general, but also because it demonstrates how quartz can form naturally, even at low temperatures. These conditions are very different to the low to medium temperature conditions previously considered necessary for quartz crystal formation. The mechanism that brings about quartz deposition and concomitant gypsum corrosion is connected to the reduction of sulphates to sulphides in a phreatic environment, and it may be one of the most important mechanisms involved in the embryonic stages of karst cavity origin in gypsum.

4. Climatic influence on the chemical deposits

Climatic factors have a strong influence upon what type of chemical deposit can be found in a gypsum cave (Calaforra et al, 1992; Calaforra, 1996). In general speleothems are less abundant in cavities in gypsum than they are in limestone caves, though some exceptions do exist. As described above, two broad types of chemical deposit can be seen in gypsum caves, these being gypsum speleothems and calcium carbonate (normally calcite) speleothems. Some caves present both deposit types simultaneously, while other caves present just one or the other. The depositional mechanisms of the two minerals are totally different in the karst environment: gypsum can only be deposited through supersaturation due to evaporation, while calcite is deposited in response to the release of carbon dioxide into the cave atmosphere or as one effect of incongruent dissolution.

These mechanisms are influenced in different ways by climatic variables, and therefore the local climate dictates the kind of chemical deposit that may develop in any given cave. There are no speleothems at all (either calcite or gypsum) in the polar regions, because extremely low temperatures prevent evaporation and, hence, deposition of gypsum. Moreover, during periods of thaw the rapid flow of water with minimal mineral content does not encourage the growth of calcite speleothems. The only chemical deposit so far observed under these conditions is a distinctive form of gypsum powder, which accumulates over ice flows during the winter periods (Forti, 1990).

Calcite speleothems in gypsum caves are found mostly in temperate humid areas, where the hyperkarst mechanism of gypsum corrosion (Forti & Rabbi, 1980) is particularly active. Gypsum speleothems are also normally present in these regions, especially, in those parts of caves (bases of pits, narrow "squeeze" passages, etc.) where stronger air currents facilitate evaporation and consequent gypsum supersaturation As the climate becomes less mild, calcite deposits tend to become predominant, until they are the only ones present. This is obviously due to a progressive diminution of the possibility of evaporation.

In areas of hot, arid climate, such as Sorbas (Spain), New Mexico and Arizona, gypsum speleothems are widespread and may grow to a large size, while carbonate formations are effectively absent. The absence of calcite speleothems reflects the fact that the arid climate prevents development of vegetation cover over the gypsum, minimising the possibility of high carbon dioxide contents in infiltration water, and therefore hindering the process of hyperkarst corrosion of gypsum. The only possible exceptions are deep drainage tubes where transported organic materials (essentially vegetation) can accumulate during flooding episodes. This material oxidizes during dry periods, supplying the environment with the carbon dioxide that is necessary for the development of carbonate crusts on conduit floors.

In the tropical environment there is a general balance between the presence of carbonate and gypsum concretions. This reflects both the great quantity of vegetation that covers most of the surface, and the extremely hot climate.

It is worth noting that calcite speleothems in gypsum caves can provide excellent palaeoclimatic indicators. In fact, in some Siberian gypsum caves, the mere presence of such calcite speleothems, now in an advanced state of degradation, indicates clearly that the host cavity existed before the last glacial maximum, in a period of more favourable climate, characterized by constant water flows throughout the year. Similar indications have been found in the Sorbas caves in Spain, where residual calcite flowstone that covers pavements inside the larger caves testifies of a humid climate, very different to today's conditions.

5. Conclusions

Reports of detailed studies of chemical deposits in gypsum caves are still relatively rare, and only a few small parts of the principal gypsum karst areas have been examined systematically from this point of view. Nevertheless, on the basis of the knowledge so far gained, it is now possible to point out some distinct characteristics of these deposits, that differentiate them from their analogues in limestone environments.

What is superficially striking is the relatively small size and the limited variety (especially in terms of mineralogical, but also their morphological, variability) of most of these deposits. This may be one reason for the delay in launching systematic studies. Such studies were considered, at best, of minimal interest, if not of no scientific value at all, until only a few years ago.

Putting this aside, the few systematic studies have all demonstrated how gypsum karst posses-ses its own unique peculiarities of morphology (particularly in the case of its speleothems) and of mineralogy (in the case of the cave minerals). Therefore, it seems certain that in the near future, with continuing study of chemical deposits in gypsum caves, there will be a large increase in the number of recorded occurrences and known types.

One final aspect of extreme interest should be re-emphasised, and that is how climatic influences dominate almost absolutely during the development of chemical deposits in gypsiferous environments. The role of climatic factors is certainly far more dominant in the gypsum situation than has been verified in limestone caves in comparable climatic situations. This close relationship with climate gives deposits preserved in the gypsum environment a potentially very great importance on the basis of their potential application to palaeoclimatic studies, not just in terms of the interest held by the cave minerals themselves.

Mineral	Chemical formula	Characteristics
1 - Aluminium oxides	Al_2O_3	Polymineral flowstones with opal, sulphur and iron oxide
2 - Bassanite	$CaSO_4.\_H_2O$	White powdery deposits on gypsum
3 - Brochantite	$Cu_4(OH)_6SO_4$	Emerald green crusts associated with devilline and penninite
4 - Brushite	$CaHPO_4.2H_2O$	Yellow pulverescent deposits on guano
5 - Calcite	$CaCO_3$	Various speleothems
6 - Carbonatoapatite	$Ca_5(PO_4,CO_3)_3(OH)$	Yellowish crusts on calcitic concretions in contact with guano
7- Celestite	$SrSO_4$	Small crystals over a crust of iron and manganese oxides/hydroxides
8 - Chloromagnesite	$MgCl_2$	Dispersed within fibres of epsomite
9 - Devilline	$Cu_4Ca(SO_4)_2(OH)_6.3H_2O$	Emerald green crusts associated with brochantite and penninite
10 - Epsomite	$MgSO_4.7H_2O$	Acicular crystals on mud
11 - Iron oxides/hydroxides		Large crusts, stalactites and stalagmites, with limonite goethite and Mn oxide
12 - Fluoroapatite	$Ca_5(PO_4, CO_3)_3F$	Golden crusts with carbonato-apatite on fossil remains
13 - Gypsum	$CaSO_4.2H_2O$	Speleothems, crystals
14 - Goethite	$FeO(OH)$	Large crusts, stalactites and stalagmites with limonite and Fe and Mn oxides
15 - Ice	H_2O	Stalactites, stalagmites, crystals
16 - Lepidocrocite	$FeO(OH)$	Minor component of stalactites and stalagmites of goethite, gypsum and opal
17 - Limonite		Large crusts, stalactites and stalagmites, with goethite and Fe and Mn oxides
18 - Manganese oxides		Large crusts, stalactites and stalagmites with goethite limonite and Fe oxide
19 - Mirabilite	$Na_2SO_4.10H_2O$	Stalactites
20 - Opal	$SiO_2.nH_2O$	Thin crusts and coralloids
21 - Penninite	$(Mg,Fe,Al)_6(OH)_8(Si,Al)_4O_{10}$	Tiny crystals corroded anhydrite
22 - Quartz	SiO_2	Skeleton euhedral druses over corroded gypsum
23 - Rhodrochrosite	$MnCO_3$	thin crust over calcite speleothems
24 - Sulphur	S	In polymineral concretions with opal and oxides of aluminium and iron
25 - Sylvite	KCl	Stalactites

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Chapter I.8

GEOMORPHOLOGICAL ASPECTS OF GYPSUM KARST AREAS WITH SPECIAL EMPHASIS ON EXPOSED KARST

Ugo Sauro

1. Medium- and large-sized forms

Medium- and large-sized gypsum karst landforms are similar in many respects to those found on carbonate karst. However, there are also some differences. This chapter will review the typical landforms of gypsum karst, stressing the similarities and the differences when compared with carbonate karst forms, and discussing their morphogenetic peculiarities.

In gypsum karst areas it is also commonly possible to recognise landforms produced by erosion due to surface flow and the effects of fluvial deposition, both of which are to some degree related to the presence of lenses and layers of other rock types. Landforms produced by different types of landslides are also present.

Among the typical karst landforms, the following have been recognised:

1) dolines,
2) blind valleys,
3) polje-like depressions,
4) subsidence and collapse basins in rocks that overlie gypsum.

1.1. Dolines

Gypsum karst includes doline types that are similar to those developed in carbonate terrains. Authors who have described the geomorphology of gypsum karst areas have listed the following types:

1) shallow, flat floored, dolines,
2) saucer-shaped dolines,
3) bowl-shaped dolines,
4) funnel-shaped dolines,
5) pit-like dolines
6) asymmetrical slope dolines,
7) multiple or composite forms formed by the fusion of two or several simple forms,
8) chains of dolines, and corridors derived by the fusion of many dolines,
9) intermediate forms between dolines and small blind valleys.

Dolines exhibit a wide range of sizes: diameters vary from a few metres to several hundred metres; depths range from a few decimetres to nearly one hundred metres (Fig. 1).

It is noteworthy that very small dolines are present only where pure gypsum crops out, and the depressions are adjacent to each other, constituting a honeycomb karst. Populations of very small dolines have been described in the Italian Dolomites by Bini (1983) and in the western Alps

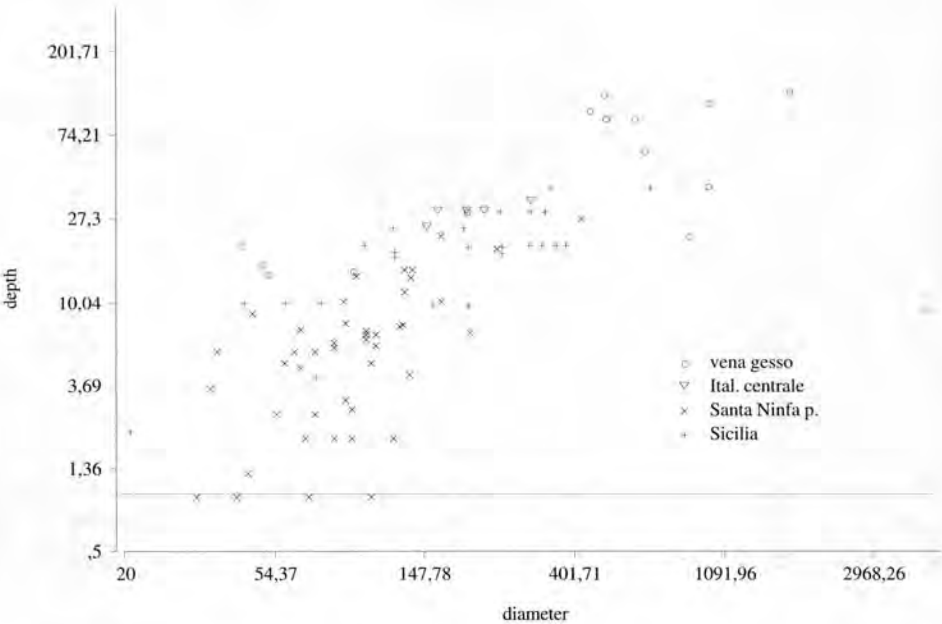

Fig. 1. Scattergram showing the inter-relations of depth to maximum diameter of some doline populations in gypsum karst areas of Italy. The scales are logarithmic (log $_e$). The data are derived from Sauro (1987) and Meneghel (in Agnesi et al., 1989). Some of the larger forms are blind valleys.The population with larger forms is that of Vena del Gesso, while the medium-sized and smaller forms are those of the Santa Ninfa plateau in Sicily, where a detailed morphometric analysis has been performed.

by Capello (1955).Typical populations of honeycomb doline karst, with dolines ranging in diameter from a few metres to several tens of metres are known in the Baisun-Tau mountain area, between the Uzbekistan and Tagikistan republics (Bernabei & De Vivo, Eds, 1992), and in the Alps of Albania (Bassi & Fabbri, 1996).

Intermediate features between karst and fluvial forms are probably better recognizable on gypsum than in most carbonate terrains. Many dolines also show the characteristics of small blind valleys. These forms are generally elongated to follow regional surface slopes. They display a significant difference between maximum depth (difference in elevation between the highest point of the watershed and the bottom of the depression) and minimum depth (difference in elevation between the lowest point of the rim of the depression and its floor). Basin shape is asymmetrical, with a more extended slope on the uphill side and a narrow but generally steeper slope on the downhill side.

Chains of dolines that are clearly the result of the "drying up" of fluvial valleys are also easily recognizable. In general the dolines within these multiple features are elongated along the axis of the chain (Fig. 3).

Lying between the different forms and features associated with dolines or "nested" inside

Fig. 2. View of a gypsum plateau in the Baisun-Tau mountain area, between the Uzbekistan and Tagikistan republics. The honeycomb structure of the karst depressions is evident (Photo of "La Venta" Association).

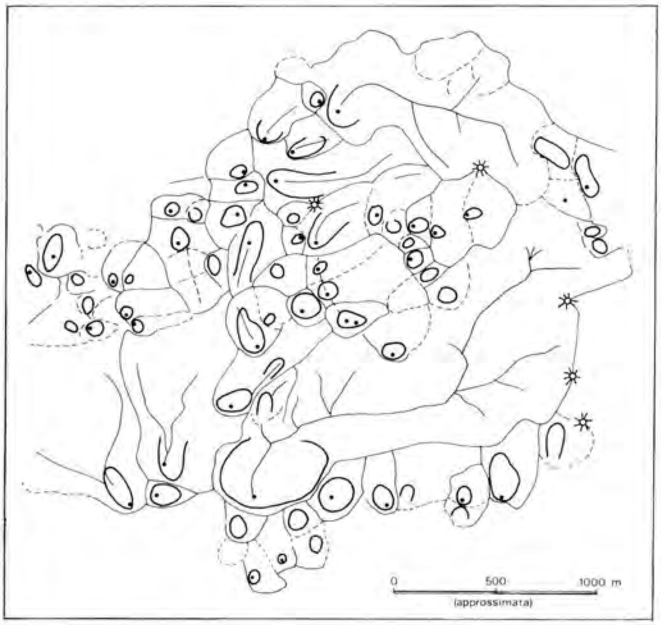

Fig. 3. Sketch of the closed landforms in the plateau area of Santa Ninfa. Typical circular dolines, blind valleys and intermediate forms are well displayed. Chains of dolines are also recognized, having developed from pre-existing blind valleys. The basin watersheds and dome-like hills are also indicated (after Agnesi et al, 1989).

basins, are examples of small fluvial incisions (such as gorges and canyon-like valleys), different types of karren, pits or shafts, cave entrances and swallow holes.

1.2. Blind valleys

Several different types of blind valley have been recognized in gypsum karst:

- valleys that are cut into insoluble sediments, such as clays or other clastic materials, and end at the contact of these rocks with gypsum outcrops, where a swallow hole is active (examples are numerous in the Northern Apennines, Northern Caucasus, the Baisun-Tau mountains of central Asia, and elsewhere);

- valleys with an upstream part lying on insoluble sediments, continuing for several tens or hundreds of metres incised into gypsum outcrops, until ending at a swallow hole (as demonstrated by some valleys in Sicily, such as lo Sfondato, near Porto Empedocle);

- valleys cut completely or almost completely across gypsum outcrops (also demonstrated by some valleys in Sicily, such as the Valle del Biviere, in Santa Ninfa);

- small valleys, or valley-dolines, cut completely within gypsum outcrops, which continue downstream as chains of dolines (some valleys in Sicily in the Santa Ninfa area; see also the sub-chapter on dolines above).

1.3. Polje-like depressions

Polje-like landforms are also present in gypsum karst areas. Most of them are open, but some are partially closed around "ponors". Examples include the polje of Bambini in Greece, the open palaeo-polje of Sant Maximin in France (Nicod, 1993), and some of the poljes in Sicily (such as il Pantano, to the west of Siculiana Mare). In the Alps a glaciokarstic polje has been described (polje of La Valoire; Nicod, 1976). Polje-like depressions in intrastratal gypsum karst areas are described by Goburnova (1979). See also Chapter I.10.

1.4 . Subsidence and collapse basins in rocks overlying gypsum

Some "karst-like forms" are induced upon non-karstic rocks by intrastratal karst development within gypsiferous and/or saliferous rock units. If underground water is able to reach such gypsum or rock salt, dissolution occurs and there is a loss of volume, creating voids in the buried sequence. As a result, both subsidence and collapse phenomena may take place, locally resulting in visible effects at the topographic surface.

Common forms that originate due to subsidence are closed basins. These may be very large but shallow, and many of them are occupied by lakes. In Sicily there are numerous lakes of this type, with surfaces ranging from a few hundred square metres to about $2km^2$ (Agnesi et al, 1987; Trevisan & Di Napoli, 1937). The lakes are susceptible to undergoing rapid changes in shape and size caused both by progression of the subsidence and by erosional processes. The Pergusa lake, near Enna in Sicily, has an area of $1.83km^2$ and a maximum depth of only 4.6m.

Landforms that originate due to collapse are generally much smaller, but commonly show a higher depth/diameter ratio. In the braided bed of the Tagliamento River (Southern Alps), many collapses have occurred during the present century. The largest described was about 40m in diameter and 20m in depth (Gortani, 1965). More details of karst landforms in areas of intrastratal karst, and mechanisms of collapse development, are provided in chapter I.10.

2. Positive and/or residual forms

Among the positive and/or residual landforms that result from the interaction between active processes (tectonic forces, gravity, weathering and denudational effects) and passive influences (lithological and structural guidance), the following may be listed:

1) outliers,
2) cone-like hills
3) dome-like hills,
4) mesa-like tabular blocks,
5) plateaux,
6) breccia pipe hills.

2.1. Outliers

Outliers are isolated remnants of gypsiferous rock units that are left sitting upon underlying clay rock units after the parent mass breaks into fragments that slide apart. Some of them are spectacular parallelepiped-shaped or pyramidal hills, such as the Rocca di S. Paolino, of Sutera in Sicily.

2.2. Cone-like hills

Cone-like hills are relatively small hills that develope inside honeycomb karst, and are comparable in appearance with the conical karst of carbonate regions.

2.3. Dome-like hills

Dome-like hills are more or less hemispherical hills, comprising homogeneous gypsum masses. Their origin is not yet clear, but it probably relates to flowage of gypsum in response to one-sided unloading during exposure, and inhomogeneous stresses imposed by tectonics (see Chapters I.1 and I.9). Unusual weathering processes affecting the uppermost gypsum layers might also play a part in their development. Some dome-like hills have also developed due to the protective effect of thin evaporitic limestone cap rocks, which prevent dissolution of the underlying gypsum (Agnesi et al, 1989).

2.4., 2.5. Mesa-like tabular blocks and plateaux

The mesa-like tabular blocks and the gypsum plateaux are relatively large expanses of gypsum with nearly horizontal upper surfaces, generally delimited laterally by erosional or fault scarps.

2.6. Breccia pipe hills

Breccia pipe hills are areas of relatively high relief that result from the selective denudation of breccias composed of different rock types. The breccias originate due to collapse of gypsiferous beds and other rocks into cavities formed within deep-seated gypsum beds. Such breccias commonly have a pipe-like form and locally they can offer more resistance to erosion than do the surrounding rocks.

3. Morphogenetic aspects of dolines and dry valleys

Morphogenetic processes producing karst landforms in gypsiferous rocks are similar to those that are active in carbonate terrains. The following types of doline have been distinguished:

1) normal solution dolines;
2) dolines originated by the evolution of a swallow hole;
3) dolines originated by collapse phenomena;
4) alluvial and/or piping dolines;
5) subsidence basins and dolines.

Whereas in many carbonate areas most dolines appear to fit within type 1), in areas of exposed gypsum most dolines seem related to type 2). On gypsum outcrops water infiltration tends to relate to a few well-defined sink points, and not to a dense system of small openings as is more common on carbonates. Probably there are two main drainage system elements: nearly horizontal, influenced by clay layers and lenses, and nearly vertical, guided by joint (and other) fissures. The typical honeycomb patterns are probably related to the latter.

The structures of epikarsts developed in carbonate and in gypsum sequences are dissimilar. In gypsum, most fractures are sealed near the surface, so most surface water penetrates and flows through a few medium-sized and large cavities. This characteristic is also indicated by the negligible storage capacities of gypsum epikarst and by the very short time lag between precipitation and peak discharge from the underground drainage systems.

Thus, the configuration of slopes within a doline in gypsum is influenced both by normal slope processes and by chemical erosion at the soil/rock or rock/atmosphere interface. However, the rock surface is not a real barrier to the water: some water is able to penetrate for a distance of between a few centimetres and a few metrers into the interstices between crystals. Interstitial water favours loss of mass, exchange of salts and recrystallization of the gypsum, and contributes to surface lowering in general.

In literature describing gypsum karst, many authors have expressed astonishment at the engulfment capacity of swallow holes in blind valleys and dolines. In many blind valleys there are large quantities of clay and gypsum fragments that are removed by streams during floods. It is difficult to understand why this material does not obstruct the underground channels, which appear to remain constantly active, even when they contain large amounts of fill. Among the possible explanations for such drainage capacity it is important to remember the process of mass wastage due to the dissolution of gypsum clasts and also, perhaps, a possible auto-lubricant capacity provided by mixtures of gypsum, solvent water and clay (Marinelli, 1917). Ghosts of gypsum pebbles have been observed in the cave deposits of Santa Ninfa in Sicily (Bini, 1989). Dissolution of origi-

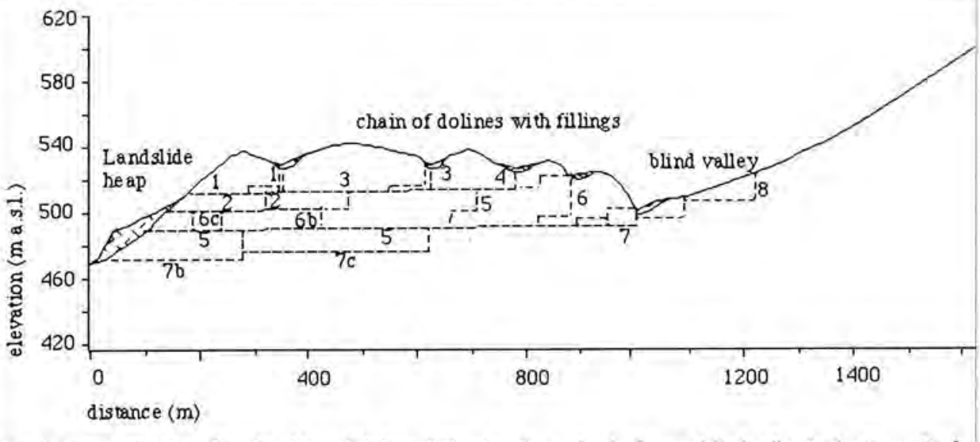

Fig. 4. Longitudinal profile of a chain of dolines following the path of a former blind valley in the Santa Ninfa plateau (Sicily). It is seen how the altitudes of the doline bottoms decrease upstream. The first and most active closed basin of the chain is an intermediate form, between a small blind valley and a doline. The form of the underground drainage network is hypothetical and reflects the possible influence of clay beds and lenses. Small springs fed by the karst system have probably induced a landslide on the scarp to the left.

nal gypsum pebbles produced pebble-shaped voids, increasing the porosity of the deposits and facilitating their erosion during floods.

In many alignments or chains of dolines, each doline seems to have originated due to development of a swallow hole at the end of a blind valley. The first doline in the chain to develop is that at the downvalley limit, while the farthest upvalley doline is the youngest and represents the end of a small, still-active blind valley.

The phenomenon of swallow point retreat within blind valleys in carbonate areas has been described in many areas, including the Classical Karst. On gypsum, it is commonly clearly observable that the slope of the longitudinal profile along a chain is counter to that of the old valley floor. This means that the altitudes of the lowest points of the bottoms decrease from the oldest to the youngest dolines in a chain (Agnesi et al, 1989; Sauro, 1995, Fig. 4).

In the Vena del Gesso of the Northern Apennines other interesting aspects of blind valleys and doline evolution are recognized. For instance, a palaeo-erosion surface cuts a homoclinal sequence that includes a thick gypsum formation. The latter rock unit is more resistant to erosion than adjacent units and tends to emerge as a structural ridge, perhaps best described as a "bevelled cuesta", dipping towards the plain of the Po. The ridge is dissected by the major valleys that provide water gaps through it, but some local water courses end as blind valleys at the contact with the gypsum ridge. Large and deep dolines are present on the ridge itself.

4. Genetic aspects of subsidence and collapse basins

The evolution of subsidence and collapse basins is worthy of individual study in each morphostructural situation, but only two examples are considered here. The first is that described by

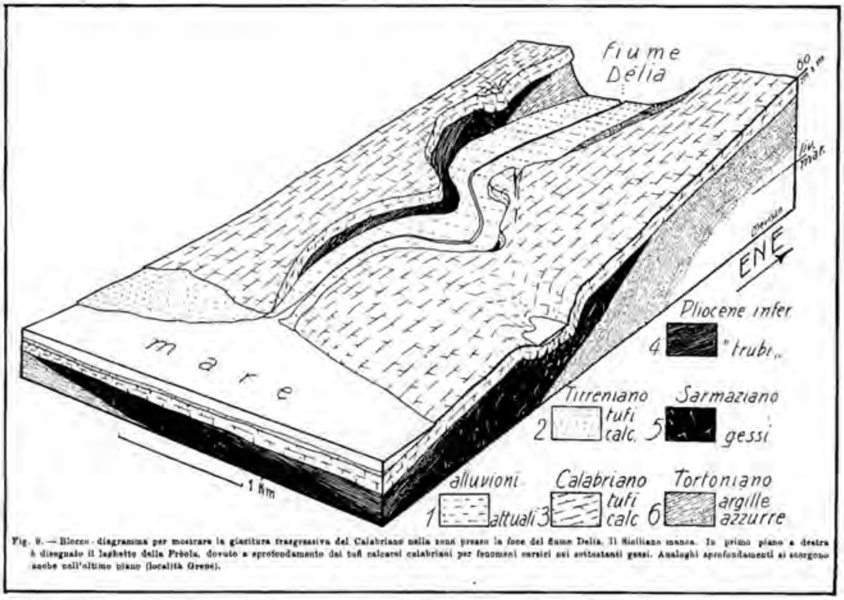

Fig. 5. The subsidence basin of Preola lake in Sicily is the result of the subsidence of a Lower Pleistocene calcarenite formation. The underlying gypsum, cut by an erosion surface, is partly dissolved by the waters of the Delia River, which infiltrated along the course of an entrenched meander (from Trevisan & De Napoli, 1937).

Trevisan & Di Napoli (1937), in the Preola Lake depression in Sicily. The lake basin is developed within Lower Pleistocene marine calcarenites, slightly more than 10m in thickness, that cover an erosion surface cut by a marine transgression. This erosion surface cuts across a homoclinal sequence that includes about a hundred metres of gypsum. The Delia River valley has entrenched into the gypsum. Along the course of the river bed lateral circulation has favoured preferential dissolution of gypsum below the calcarenite cover, with consequent subsidence of the overlying beds and development of a closed basin (Fig. 5).

The second example is of collapse basins on the bed of the Tagliamento River in the Southern Alps. Here there are gypsum lenses covered by fluvial deposits, most of which are pebble-dominated and locally cemented to form conglomerates. Underground water within the fluvial deposits dissolves the underlying gypsum, creating cavities that induce sudden collapses, with concomitant development of ephemeral "alluvial dolines" in the river bed.

5. Aspects of doline plateaux evolution

Two main models for the evolution of doline plateaux in gypsum can be described by, referencered to real situations observed in Sicily. In the Santa Ninfa plateau, which consists of a gently sloping homoclinal surface delimited on three sides by scarps, some remnant outcrops of the denuded overlying rock unit remain. This is the Trubi Formation, which consists of marly limestones and clay. A fluvial network developed here before the underlying gypsum was exposed. This network was superimposed upon the underlying gypsum, with subsequent development of a sequence of blind valleys and doline chains. Now both forms co-exist, but in some areas the dolines have colonised the entire surface and have now coalesced to produce a type of honeycomb karst. The evolutionary sequence passed from a fluvial morphology, through an entrenched karst, into a denuded karst.

On the Serra Ciminna plateau, which is a nearly tabular surface delimited on all sides by scarps, gypsum is covered (at least locally) by permeable sand and pebble deposits. The top of the gypsum is an erosion surface that was affected by karst processes both during the previous phase of exposure and after the covering episode. Water can circulate within the cover rock to dissolve the underlying gypsum. Uplift of the plateau has favoured the enlargement of fissures and the development of karren and dolines. The slopes of some dolines comprise tabular karren-covered surfaces separated by large grikes, and in other places there are miniature stone forests with rock pedestals several metres high.

No detailed study of a plateau with typical honeycomb patterns of dolines has been described. It seems that in some plateau areas (such as in the Alps of Albania) there is a nearly cylindrical pit at the bottom of each basin. It may thus be supposed that during the last stage of denudation of the overlying formations (limestones or others permeable rocks) a dense and regular network of small vertical pits (pipes) developes, probably guided by the joint network in the gypsum. This network of vertical cavities allows evacuation of gypsum solutions and sustains doline evolution.

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Chapter I.9

WEATHERING CRUST AND KARREN ON EXPOSED GYPSUM SURFACES

Tommaso Macaluso & Ugo Sauro

Abstract

The evolution of gypsum bare rock surfaces is the result both of volume changes of the outer rock layer and mass wasting by dissolutional processes. Some unusual weathering processes induce an increase in the volume of the outer gypsum layer, resulting in the development of a "weathering crust" and of characteristic forms such as small ridges and bubbles. However, the more typical erosional forms are dissolutional ones of karren type, which are commonly interconnected, or superimposed upon the previously described forms.

In this chapter a classification system is proposed and discussed, within which the magnitude, order and geometry of the different karren forms are outlined, and the related lithofacies and main morphogenetic processes are examined.

1. The special geo-dynamic environment of exposed gypsum surfaces

Bare rocky surfaces developed upon gypsum are of interest due to the unusual, and as yet poorly studied, weathering phenomena that they illustrate. Most rocky surfaces on gypsum are exposed as a consequence of soil erosion induced by the effects of forest clearance, fires, or overgrazing by sheep and goats.

On many gypsum surfaces there is a distinct "weathering crust", characterized by polygonal fissuring and other small- and medium-sized forms that indicate the phenomenon of volume increase within the outer rock mass for a thickness between a few decimetres and several metres. Development of this crust is not related to the bedding or other structural features, but it seems to reflect the progression of a "weathering front" governed by the local topography. Within the crust there is clear evidence of a tendency towards the sealing both of pre-existing and of newly formed fissures. This property of "self-sealing" explains the scarcity of grikes on most exposed gypsum surfaces.

Different morphological types that have originated due to these weathering processes have been recognized, the best known of which are pressure ridges and gypsum bubbles (Macaluso & Sauro, 1997a). In Sicily intermediate-sized forms, between mega-bubbles and dome-like summits, some tens of metres in diameter and several metres high, have been found (fig. 1).

The dome-like summits of many hills in gypsum are reminiscent both of some types of inselberg summits in granitic rocks, and of the form of mega-bubbles in gypsum. Development of these dome-like forms is probably caused by the creation of isotropic stress fields. In this way the weathering crust minimizes the influence and effects of pre-existing structural elements, such as bedding planes and various fractures.

The causes of this change in the character of the outer rock layers are not yet fully under-

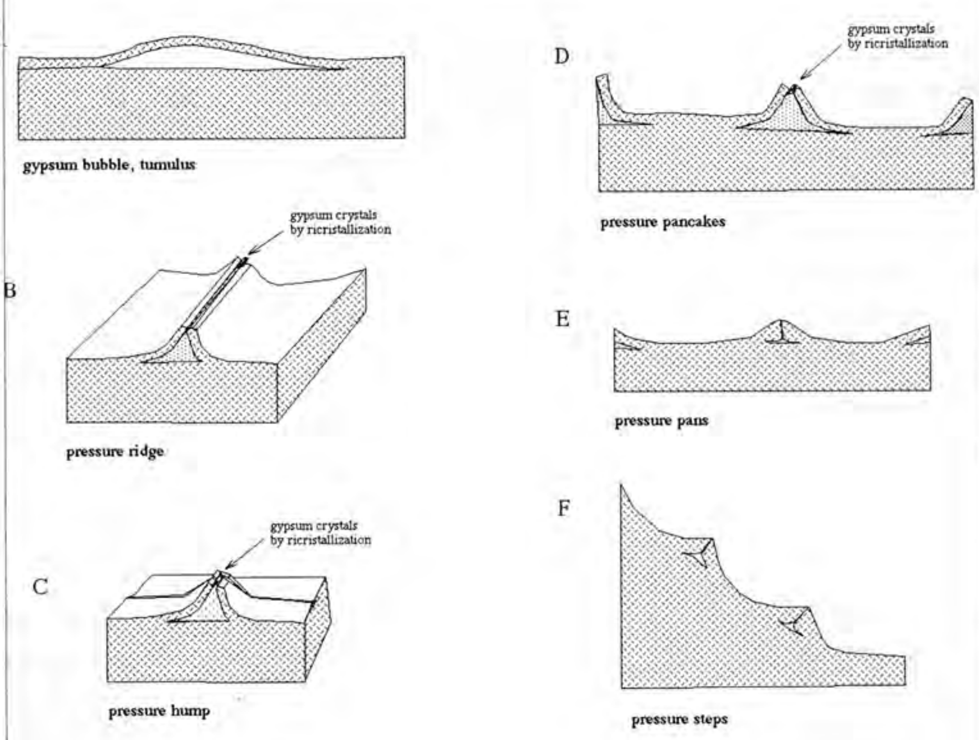


Fig. 1 - Morphological types recognised on the on the "weathering crust" of the exposed rocky surfaces of Sicily: a) the rocky polygons, often with bended fringes, b) the gypsum bubbles, c) the pressure ridges, d) the pressure humps, e) the pancakes, f) the pressure pans and the pressure half pans, g) the steps.

stood. One process that could play a role in the volume increase is recrystallization of the outer gypsum layer. Such gypsum recrystallization is probably linked to a seasonal cycle of pore water supply, typical of the Mediterranean climatic regime. The water solutions moving inside the pores are also expression of a mass transfer of salts, that may favour the accretion of the crystals. In addition to this essentially chemico-physical process, various types of biological activity may also have an important role in gypsum weathering and recrystallization.

2. Forms produced by dissolution

Generally the most common weathering forms on gypsum surfaces are dissolutional ones of karren type. Most karren are relatively small forms. However, they are first and foremost an expression of the individual styles and settings of the natural processes that are active during landform evolution. So, it is important to analyze them, because each karren type coincides with a locally unique micro-environment that is defined by a specific physico-chemical mechanism.

Simple dissolution by water is the fundamental process driving the development of karren in evaporitic rocks.

The classification of karren in evaporitic rocks adopted here is derived partly from that described in previous papers (Macaluso & Sauro, 1996; 1997b).The forms recognized are distinguished on the basis of their size as nano-forms, micro-forms, small forms and meso-forms. The adopted size scale is relative and mostly derived from the literature; it is not based on the standardised physical scale.

2.1. Nano-forms

The nano-forms are those in which all dimensional parameters are between a few microns and less than 1mm (Moses, 1996). Whereas in carbonate rocks most nano-forms are the result of biological activity, in gypsum some of them are linked directly to the size and structure of the gypsum crystals (Forti, 1996).

2.2. Micro-forms

Micro-forms are defined here as those forms in which at least two of the three dimensional parameters (length, width, depth) are of the order of one to a few millimetres. The volume of a micro-form is generally less than one cubic centimetre.

Micro-forms are represented by micro-rills, micro-ridges, micro-meanders, micro-pits and micro-conduits. Micro-rills are very small, nearly linear grooves, one to two millimetres wide, up to several centimetres long and less than two millimetres deep. Their cross-profiles are U-shaped with only a slightly concave bottom, and with sub vertical and locally overhanging sides. Bundles of micro-rills are commonly well developed on very fine-grained lithofacies. Micro-ridges are very small ridges, about one millimetre wide, and between a few millimetres and several centimetres long. Micro-meanders are very similar to micro-rills, though they can be larger. The main difference is in their patterns, which show typical meanders, consisting of loops with curvatures between a few millimetres and about one centimetre radius. An asymmetry is evident between the two sides of the loops, with a steeper slope on one side. These forms are commonly organized into sub parallel bundles on sloping rocky surfaces. Isolated examples may be found on the floors of dissolution runnels.

Micro-loops consist of very small twisting grooves without significant continuity. This morphology perhaps reflects the crossing of many forms, conferring a scrollwork appearance on some small rocky surfaces. Micro-pits are small, nearly circular hollows, with a diameter less than one centimetre, separated by prominent and commonly asymmetrical sharp edges. Some of these forms may be comparable with the mini-craters described below. Micro-conduits are rarer forms that have been observed on laminated balatino gypsum, especially in coastal environment.

2.3. Small dissolutional forms

Small dissolutional forms are defined here as those in which at least two of the three dimensional parameters are measured in centimetres but are in general less than one metre. The small

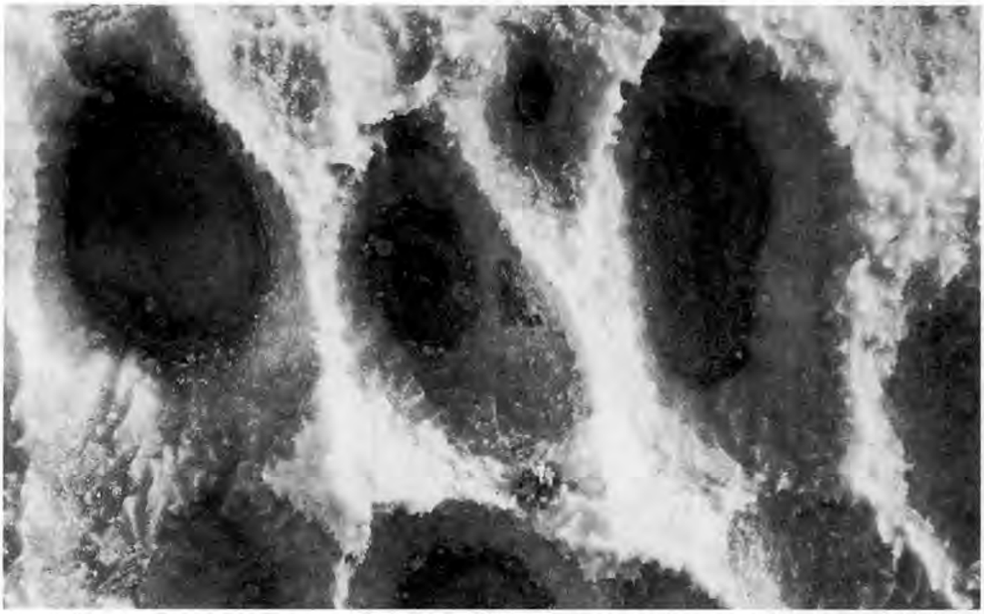


Fig. 2 - Minute rain craters on gypsum. The slopes of the minute craters show microrills (Verzino, Calabria, Italy).

forms include mini- rain craters, rillenkarren, mini-spitz (or mini-spike), dissolution levels, heel-print karren, scallop-like karren, meandering rills, dissolution runnels, meandering runnels and flared runnels.

Beside these forms there are some that are the result of the influence of pioneer vegetation. These take the form of small knobs and enclosures that reflect the protective influence of lichen colonies. Other forms of boxwork type are the result of selective dissolution on gypsum exposures that are crossed by veins of different minerals.

Mini- rain craters (called "rain pits" by some authors) are crater-like depressions, easily recognized on very fine-grained gypsum. Their borders are nearly elliptical or polygonal, with a diameter of 12-30mm and a depth of 1-30mm. Their cross profiles are parabolic with rounded bottoms, steep sides and sharp crests. These basins are generally located on the summits of rocky blocks and spikes, just upslope of the band of rills. They are commonly organized in multiple honeycomb complexes that look like miniature versions of a polygonal doline karst (fig. 2).

Rills, which are the most widespread of the small forms, may occur gathered into complexes on bare rock surfaces. These furrows, ranging between a few millimetres and several centimetres in width and depth, are similar to grooves cut into wood by a gouge (a chisel with a concavo-convex cross section). They originate at watersheds, or just downslope of the mini-crater zone, and extend across distances of some centimetres to several decimetres. Their cross-profiles are parabolic, while their intervening crests are sharp. The dimensions are governed by the lithology, the slope gradient and the microclimate. Widths are generally less than 20mm and depths vary between 4 and 15mm (Fig. 3).

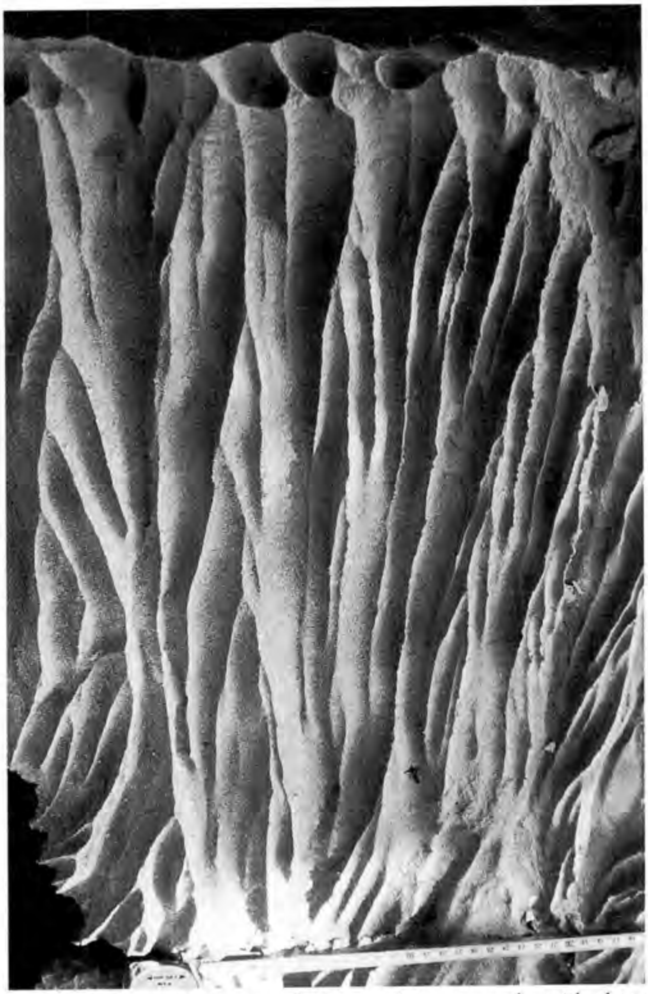


Fig. 3 - Assemblages of rills starting from a narrow crest. On the crest a few minute rain craters are also recognizable (Verzino, Calabria, Italy).

Mini-spitz (or minute-spike) are miniature peaks with sharp points, that develop in the nodal points between the borders of contiguous rills and/or mini- rain craters. They are common both in alabastrine and laminated balatino gypsum and also in salt, where they show the highest relief energy. These points cannot be considered elementary forms in themselves, but are the consequence of the interference of elementary forms such as mini-craters and/or rills.

Dissolution levels (Ausgleichfläche in German) are nearly horizontal surfaces of various sizes, that are not related to the bedding planes. Such levels are produced by diffuse dissolution from a homogeneous water sheet flowing slowly across the surface. Their development is linked to a slackening of the erosional flux, governed by local factors such as slight changes of gradient and impediments to downslope flow.

Heel print karren (Trittkarren in German) are small hollows with a nearly flat bottom, that are open in the downslope direction and delimited upslope by steep horse-shoe-shaped scarps, simi-

Fig. 4 - Gypsum pavement initially developed under a cover of permeable sediments subsequently removed by erosion (Serra Ciminna, Sicily).

lar in appearance to the heel prints of a boot. The upper edges of these scarps are commonly the lowest rims of the planar bevels of higher heel prints. In fact, heel prints can occur in swarm-like assemblages, comparable in appearance to those of crescentic dunes.

Scallop-like karren are forms comparable with heel prints, but they do not show such a sharp differentiation between the back scarp and the planar bottom. Scallops show a large variability of widths and lengths.

Meandering rill forms are clearly linked to the transfer of water from small reservoirs within the soil or from belts affected by the splashing of waves on coastal gypsum cliffs. They are comparable with the decantation flutings of Ford & Williams (1989).

Runnels are steep-sided and round bottomed grooves, distinctly larger than dissolution rills. They present a large variability both in their cross dimensions and in their planar development (or extension). Most of these forms show a U shaped cross-profile, some with overhanging sides. On gently sloping surfaces their trend is commonly sinuous or meandering (Mäanderkarren in German), while on steeper slopes they tend to become linear.

Flared runnels are larger runnels, commonly with nearly flat bottoms and steep sides, that developed starting from the depressions of rounded Karren, following soil erosion.

Small knobs and enclosures reflecting the protective influence of lichen colonies are also common on some surfaces. The enclosures present circular patterns and surround closed depressions of pan type.

Between the boxwork type forms, or related to them, the following types resulting from selective dissolution have been observed: a) polygon pans or closed depressions, completely encircled by small dikes or veins of less soluble material; b) dissolution levels originated by the damming influence of less soluble veins downstream of the developing form.

2.4. Meso-forms

Meso-forms are defined here as forms in which at least two of the three dimensional parameters are between a metre and ten metres.

The most typical meso-forms are dolines, which are not discussed here. Rundkarren assemblages, some gypsum pavements, and some types of stone pinnacle are typical karren meso-forms.

Fields of rundkarren are quite common on gypsum. The initial development of these assemblages of forms may be linked to interface dissolution related to differences in the thickness and permeability of the cover. On semi-covered rundkarren the development and preservation of spikes is due to the upper parts intercepting only direct rainfall, while inside the depressions, partly filled by permeable regolith, there is much more water, derived from the slopes above. The form size is governed both by lithofacies and by the nature of the cover. Small-sized rundkarren are also present on some gypsum outcrops, but these must be classified as small forms.

Gypsum pavements represent extensive assemblages of more basic forms. Many types are recognized, including rills and runnels gypsum pavements on pseudo-structural slopes of macrocrystalline gypsum, rill, heel print and runnel pavements on dome-like hill tops of alabastrine gypsum, and "gypsum-Tischen" ("tables") with relatively flat surfaces delimited by grikes (Fig. 4).

Unusual landscapes compatible with the pinnacle karst of carbonate areas have also been found. Their origin is probably linked to interface dissolution due to water flow inside a cover of loose, porous sediments, such as fluvial or coastal sands. The development of a "cryptokarst", with large grikes and corridors, favours "subsidence" of overlying material. Such forms have been observed in areas affected by accelerated erosion or quarrying activity.

3. Genetic aspects

The development of micro-rills and micro-ridges may be explained by density flux differentiation inside sheets of solvent water that flow slowly across rocky surfaces. It is not unusual for solvent water to move upwards, drawn by capillary tension exerted at an evaporation front (Laudermilk & Woodford 1932; Ford & Lundberg, 1987; Ford & Williams, 1989) and sometimes, possibly, driven by wind during rainfall.

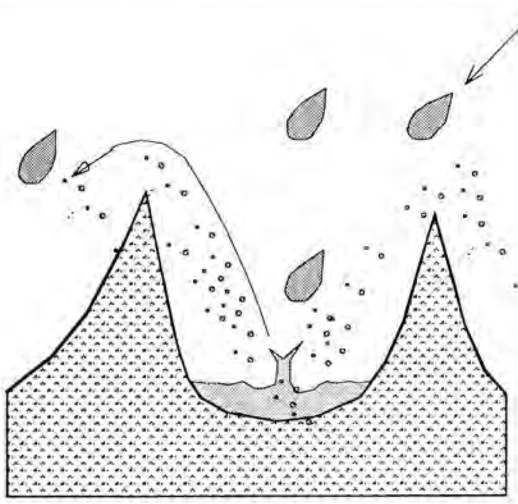
Micro-meander development is probably linked to mechanisms similar to those that operate during the outgrowth of micro-rills, by trickles fed by small water reservoirs inside soil turves (the decantation forms of Ford & Williams, 1989), or, in coastal environments, by trickles from rocky surfaces sprinkled with wave water. The presence of small granules, such as soil particles and sand, that interrupt the flow, seems to typify the conditions for micro-meander development. Such granules, lodged against small irregularities within developing grooves, obstruct the flow and promote the formation of meanders (Agnesi et al, 1986). Micro-meanders may also evolve as covered forms, in the bottom of soil-filled runnels.

Among the small forms, the genesis of mini- rain craters is probably due to "splash dissolu-

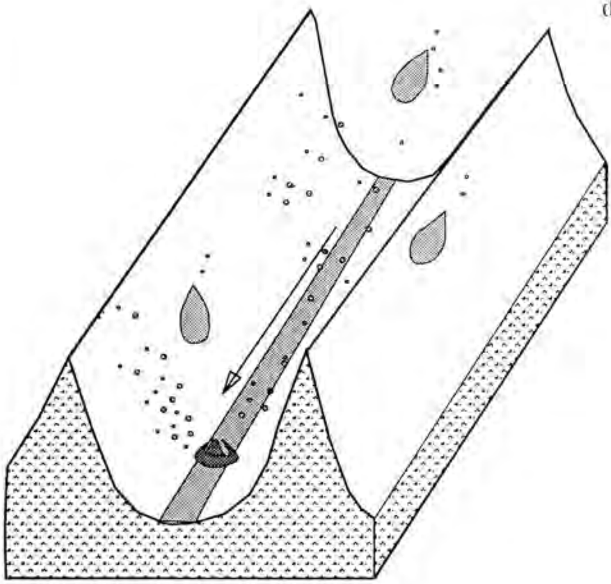
KARREN IN EVAPORITIC ROCKS: SKETCH OF CLASSIFICATION

SIZE	NOMENCLATURE	RELIEF	DIMENSIONS (bxdxL)mm	LITHOLOGY	GEOMETRY	PROCESSES	CONTROL	ENVIRONMENT
mc	micro-rills	negative	1*1*50-200	al. bal. gypsum	linear	solution	hydrodinamical	bare rock
mc	micro-ridges	positive	0,5-2*1*5	al. bal. gypsum	linear	solution	hydrodinamical	bare rock
mc	micro-meanders	negative	1-4*2*50-400	al. bal. gypsum, salt	linear	solution	hydrodinamical & dec.	semicovered rock
mc	micro-loops	negative	0,2*0,2*2-5	al. bal. gypsum, salt	linear			
mc	micro-pits	negative	3-10*3-6 (diam., d.)	div. gypsum	planar circular	solution	hydrodinamical	bare rock
mc	micro-conduits	negative	1-5*L variable	bal. gypsum	planar circular	solution	structural (fractures)	various
sf	mini-rain craters	negative	10-20*5-30	al. bal. gypsum, salt	planar circular	solution	hydrodinamical	rocky spikes
sf	rills	negative	3-30*2-20*200-1000	div. gypsum, salt	linear	solution	hydrodinamical	bare rock
sf	mini-spitz	positive	20*10-30	al. bal. gypsum, salt	linear	solution	hydrodinamical	bare rock
sf	solution levels	negative	large variability	al. bal. gypsum, salt	planar circular	solution	hydrodinamical	bare rock
sf	heelprint Karren	negative	50-200*5-30*50-200	div. gypsum	planar circular	solution	hydrodinamical	bare rock
sf	scallops	negative	10-80*5-20*20-100	gypsum al., bal.,	linear	solution	hydrodinamical	bare rock
sf	meandering rills	negative	large variability	gypsum al., bal.,	linear	solution	hydrodinamical & dec.	semicovered rock
sf	runnels	negative	30-300*30-150*200-40 m	div. gypsum	linear	disint.& solution	hydrodinamical & dec.	semicovered rock
sf	meandering runnels	negative	4-20*5-15*50-700	gypsum al., bal.,	linear	solution	hydrodinamical & dec.	semicovered rock
sf	flared runnels	negative	100-800*100-1 m*100-3 m	div. gypsum	planar circular	disint.& solution	complex	semicovered rock
sf	small knobs	positive	10-500*20-200	div. gypsum	planar circular	biocon; diffsol	complex	various
sf	pans in knobs	negative	*5-30*10-200	div. gypsum	planar circular	biocon; diffsol	complex	various
sf	pans in boxes	negative	10-200*5-30*10-300	div. gypsum, salt	planar circular	bulg., cal. diffsol	complex	various
sf&mf	grikes	negative	large variability	div. gypsum	linear	bulg., tensl., solution	structural (fractures)	various
sf&mf	pits	negative	30-500 (diam.)	div. gypsum	planar circular	bulg., solution, disint.	structural (fractures)	various
mf	Rundkarren	positive	large variability	div. gypsum	areal	solution & weath.	structural (fractures)	covered & semic.- rock
mf	pavements	positive	large variability	div. gypsum	areal	solution & weath.	complex	various
mf	pinnacle karst	positive	large variability	div. gypsum	areal	solution, tensl., weath.	complex	covered surface

Abbreviations - scale: mc = micro-forms, sf = small forms, mf = meso-forms; dimensions: lxdxL = width x depth x length; diam. = diameter; d. = depth; lithology: div. = divers; al. = alabastrine; bal. = laminated balatino; processes: disint. = disintegration; bulg. = bulging of gypsum by different processes; cal. = calcification; tensl. = tensional slackening; weath. = weathering; control: dec. = decantation; diffsol: differential solution; biocon: biological control.



MINI-CRATER



RILL

Fig. 5. The genesis of mini- rain craters is probably due to "splash dissolution" (figure above). The impact of raindrops focuses dissolution in the inner part of the depressions. Very small drops resulting from the impacts and the water collected on the crater floor are ejected by successive impacts. This exchange of the inner water also causes a mass transfer of the ions in solution.

From the genetic point of view rills seem to be analogous to mini-craters (figure below); nonetheless, in the craters the dissolution focus is point centred, linked to water droplet impacts, while in the rills there is a linear band of accelerated dissolution, related to a very thin water layer flowing along the bottom of the depression.

tion" that occurs on the summits: here the impact of raindrops focuses dissolution in the inner part of the depressions. Very small drops resulting from the impacts and the water collected on the crater floor are ejected by successive impacts. This exchange of the inner water also causes a mass transfer of the ions in solution (Fig. 5).

Mini- rain craters must not be mistaken for "micro-pits", described by Ford & Williams (1989), which correspond to the micro-honeycombs (or "micro-alveoli") of biological corrosion (De Fanti, 1971; Folk et al, 1973; Perna & Sauro, 1978).

From the genetic point of view rills seem to be analogous to mini-craters; the analogy being defined by the close correspondence between the diameters of the minute-craters and the widths of the rills Nonetheless, in the craters the dissolution focus is point centred, linked to water droplet impacts, while in the rills there is a linear band of accelerated dissolution, related to a very thin water layer flowing along the bottom of the depression (Fig. 5).

Dissolution level development is linked with a slackening of the solvent flux, controlled by local factors such as gentle gradients and impediments to downslope flow.

The development of heel print karren may be explained by changes in the speed of sheet water flow over the rock. In the early development stages the changes are probably due to surface irregularities. Once formed, a heel print causes an acceleration of the flux along the small scarp, and a consequent draw of the water in the upstream direction. When the flow reaches the bevel below it slows down, especially along the interface with the rock, and the water sheet thickens. The rock surface along the scarp comes into contact with a larger supply of water molecules. Thus, the scarp withdraws quickly and consequently the upper border of the bevel also enlarges upstream.

Mini-meanders of similar size to rills have been observed on steeply inclined surfaces of laminated balatino and macro-crystalline gypsum. These forms were originated by transfer of water from small reservoirs within the soil or rock fissures.

Runnels originate from concentrated water flows. The crystalline structure of the rock may influence the evolution of some runnel types. In particular, runnels on macro-crystalline gypsum with iso-oriented crystals tend to elongate along the direction of the crystals' long axes and thus, locally, they stray from the obvious trend of the topographical slope. Widths and depths of runnels are also influenced by the size of the crystals. Some runnels may reach a metre in cross-section, and should then be viewed as small gorges (meso-forms).

Forms reflecting direct water penetration into the rock, such as fissures, grikes and small pits and shafts, are widespread in carbonates but rare in evaporitic rocks. Fissures in evaporites rarely evolve into grikes, because they are sealed by precipitates or by soil sediments. Any large grikes that do form are generally related to initially open fractures caused by tensional slackening or by pressure following a volume increase within the upper "gypsum weathering crust". The widening of large grikes and corridors may also occur due to interface circulation below very permeable cover rocks, such as sands and gravels.

"Anti-gravitational" pits and shafts are not present in evaporites, because a pre-existing net of epikarstic cavities is generally lacking. In fact the development of anti-gravitational features in carbonates starts from a pre-existing net of grike-like fissures and bedding planes. The few small pits that have been observed in evaporites were generated by subsidence and/or by crystal disintegration following up-arching of the upper gypsum layers.

For these reasons epikarst in gypsum is very different from that in carbonate rocks. In general the secondary porosity of the epikarstic zone is modest, but in some cases it is possible to find fissures. These are normally nearly completely sealed at the surface, but relatively open some metres below. Very few open cavities exist between the surface and these deeper fissures.

4. Problems of classification and final remarks

The basis of the classification followed here is shown in the table, and it is hoped that it will stimulate discussion. It is certainly possible that different descriptive, morphographic, genetic or mixed criteria could be utilized. The mixed criteria chosen here are as close as possible to those that underlie the widely accepted classification of karren in carbonate rocks. At the same time they stress the uniqueness of dissolutional forms in evaporitic rocks, the effects of lithology and structure, and the local influence of micro-environmental conditions.

The more obvious differences between karren in evaporitic rocks and those in carbonates are:

- in gypsum, karren evolution is governed by specific weathering phenomena as well as by the dissolutional process;
- fractures in gypsum only rarely evolve as fissures and grikes that open to the surface; pits and shafts are rare, so epikarst is limited;
- runnels are not very common on gypsum, especially on macro-crystalline gypsum, where development is locally guided by the orientations of the long axes of crystals;
- biological processes related to pioneer vegetation and soils do not facilitate gypsum dissolution and may instead perform a protective function on the rocky surface, as do some lichen colonies;
- stone heaps and chaotic blockfields (griza), typical on some carbonate karst areas, are missing in evaporite landscapes, though some types of pavements and pinnacle karst are present.

Despite these differences there is a marked overall similarity between most of the dissolutional forms found on carbonates and those found on gypsum, in particular between hydrodynamically governed forms, such as mini- rain craters and rills. On this basis it is possible to infer that the differences between the physico-chemical process of carbonate corrosion, in which three phases are engaged, and the two phase process of simple gypsum and salt dissolution are irrelevant from the viewpoint of the appearance of the fundamental forms. Most of the differences between the morphological evolution of carbonate environments and that of the gypsum environment are probably linked to the different roles played by pedogenetic and biological processes.

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Chapter I.10

BREAKDOWN DEVELOPMENT IN COVER BEDS, AND LANDSCAPE FEATURES INDUCED BY INTRASTRATAL GYPSUM KARST

Alexander Klimchouk & Vjacheslav Andrejchuk

It is shown in Chapter I.4 and elsewhere in Part II of this volume that intrastratal karst is by far the predominant gypsum karst type. Its development may begin in deep-seated settings within rocks already buried by younger strata, and it proceeds increasingly rapidly as uplift brings gypsum sequences into progressively shallower positions. Such development commonly occurs under confined (artesian) hydrogeological conditions, that subsequently change to open conditions (phreatic-water table-vadose). The general evolutionary line of intrastratal karst is typified by progressive emergence of a sequence into a shallower position, activation of groundwater circulation and development of cave systems within karst units, commencement of gravitational breakdown and its upward propagation through overlying beds, and development of a karst landscape. These processes and phenomena progress through the directed evolution of karst types as follows: deep-seated intrastratal karst (IK) ⇒ subjacent IK ⇒ entrenched IK ⇒ denuded karst (see Chapter I.4).

One of the main characteristics of intrastratal karst is that it induces gravitational breakdown in cover beds. With the aid of processes other then simple breakdown, such effects may propagate upwards and may, or may not, reach the surface, depending upon the thickness and structure of the overburden. A karst landscape evolves when such features reach the surface. This paper considers the conditions and mechanisms of such development.

1. Vertical through structures

Among the most characteristic features of intrastratal gypsum karst are vertical through structures (VTS). The term VTS is used here to designate and encompass various complex phenomena known from gypsum karst regions all over the world and referred to as breccia pipes, vertical pipes, collapse columns, geological organ pipes, and so on. They are commonly believed to be breakdown structures, induced by dissolution of gypsum beds, propagated upwards through stratified overburden and filled with in-fallen clasts. Closer examination reveals that VTS are also hydrogeological structures, whose development is triggered by gravitational breakdown. However, sequential upward-stoping breakdown is maintained by active groundwater circulation accompanied by dissolution and suffosion. When mature, VTS drain any intercepted aquifers and serve as pathways facilitating and focusing cross-formational hydraulic communication. VTS location is commonly guided by fracture zones, so that any pre-existing hydrogeological function is normally inherited by the VTS. Groundwater circulation can be directed upwards, driven by artesian head, or downwards, in cases of gravitational percolation (leakage from perched aquifers) in entrenched and drained situations. Progressive upward stoping depends upon a continuing creation of space in the VTS occurring due to dissolution of soluble material in the breccia clasts. Open space tends to "concentrate" at the top of VTS, because infill generally subsides during the course of dissolution. Removal of unconsolidated material from VTS by suffosion processes also operates under certain conditions. The complex VTS formational mechanism (along with fracture zone guidance) explains their commonly disproportionately large vertical extent, relative to their diameter. Such a relationship would be impossible if mere gravitational breakdown alone was involved.

Vertical through structures are very characteristic, but not diagnostic, features of gypsum and salt karst areas. Similar phenomena are known, but are less common, within carbonate karsts developed under artesian conditions. Outstanding examples are breccia pipes within the Phanerozoic sedimentary succession of the Grand Canyon region, Arizona. These are believed to originate through the above mechanism (Hoffman, 1977; Huntoon, 1996) but their development was triggered by the collapse of dissolutional cavities in the deep-seated Mississippian Redwall Limestone, not gypsum. These pipes extend upwards for as much as 900m above the limestone and they are typically about 90m in diameter. Huntoon (1996) stressed that groundwater circulation through pipes (upward in this case) is vital to the stoping process, because it facilitates dissolution and removal of soluble materials (infallen carbonate blocks and soluble cements or clasts within infallen clastic blocks) in the pipe structure.

VTS probably occur more commonly in gypsum karst than in carbonate karst because the significant cavities that are required to induce initial breakdown form more readily in gypsum beds under deep-seated conditions than they do in carbonate sequences. Also, the rapid formation of vertical *dissolution* pipes, specific to entrenched gypsum karst, commonly triggers VTS development due to the effects of descending percolation (see below).The vertical extent of VTS in gypsum karst areas ranges widely, from a few tens of metres to more than 1000m, as exemplified by many observations in North America, England, Germany, the Eastern-European platform, the Urals, Siberia and China (see chapters II.2, II.3, II.9, II.11, II.14, and references therein). Quinlan (1978) noted some 5000 VTS up to 500m in depth throughout the gypsum and salt karst areas of the United States. Some 2875 VTS are recorded in coal mine areas of China (Yaory & Cooper, 1997), most of them being caused by gypsum karst, through some are triggered by dissolution in limestones. The greatest concentration of VTS is within the Xishan mine area, where 1300 VTS are recorded in 70km^2. Ford & Williams (1989) refer to the VTS that propagate from depths as great as 1200m after being induced by potash mines in Saskatchewan in Canada. Vertical through structures of great vertical extent provide one of the strongest strands of evidence in support of the wide occurrence of deep-seated karst. The widespread view that all breccia pipes are palaeokarst features is partially misleading, as they become fossilized only if their hydrogeological function ceases.

The development of vertical through structures is the most important mechanism by which surface features begin to evolve in all sub-types of intrastratal gypsum karst.

2. Factors that govern breakdown and VTS development

Breakdown mechanisms in gypsum sequences and their cover beds, and of the development mechanisms of vertical through structures in overburden are conditioned by many factors, of which the following are the most important:

1) the origin and structure of cavities in the gypsum;

2) the overall structure of a gypsum bed or sequence;

3) the structure, lithology and thickness of the overburden;

4) the hydrogeological conditions.

Most of these factors will change during the course of the geological/geomorphological evolution of a karst terrain. They are considered individually below, with references to appropriate examples.

Origin and structure of cavities in gypsum. Caves in deep-seated intrastratal karst develop under confined conditions. Gypsum beds are not good aquifers before speleogenesis begins; groundwaters commonly come into the contact with gypsum beds from underlying aquifer formations. If few or no fissures pass through the gypsum, dissolution remains localized along the base of a gypsum bed, or is focused along rare major tectonic faults that penetrate the gypsum. This can produce large cavities (such as caves described in the Zechstein gypsum of the South Hartz; see Chapter II.5). Breakdown of such cavities may trigger VTS development by means of upward stoping and continuing dissolution of infallen clasts, especially if the cavity is guided by a tectonic fault or fracture zone, facilitating upward groundwater circulation through a low permeability stratified cover.

Where lithogenetic and/or tectonic fissuring in a gypsum sequence is relatively dense and uniform, speleogenetic development is "dispersed" along many paths. This results in the formation of maze cave systems comprising relatively small conduits with no large chambers. This type of speleogenesis does not normally trigger significant breakdown, and sporadic local collapse cavities are commonly filled with clasts, being unable to propagate upwards significantly through the overburden. This reflects a failure to focus hydraulic communication through the gypsum to connect surrounding aquifers (which would create additional space) and signifies that the cavities do not coincide with pre-existing (initial) circulation paths in the cover beds. Breakdowns of this type cannot ramify to the surface from a deep-seated karst, and they receive surface expression only if they are brought into the fairly shallow sub-surface (subjacent, entrenched or denuded types of karst).

When incising valleys have established a water table within a gypsum sequence, inherited caves continue their active development due to widening of conduits at the water table. This process is particularly effective close to major surface streams, where annual fluctuations in river level periodically cause water to flood back into caves. Occasional breakdown is enhanced by the increasing widths of cavities, and old breakdowns are reactivated due to dissolution of infallen blocks and washing out of unconsolidated material. This situation is exemplified by Kungurskaya Cave, in the Pre-Urals region, where the Sylva river enters the cave during times of high flow (Fig. 1). In contrast, in most parts of the Western Ukraine valleys have incised rapidly to a level far

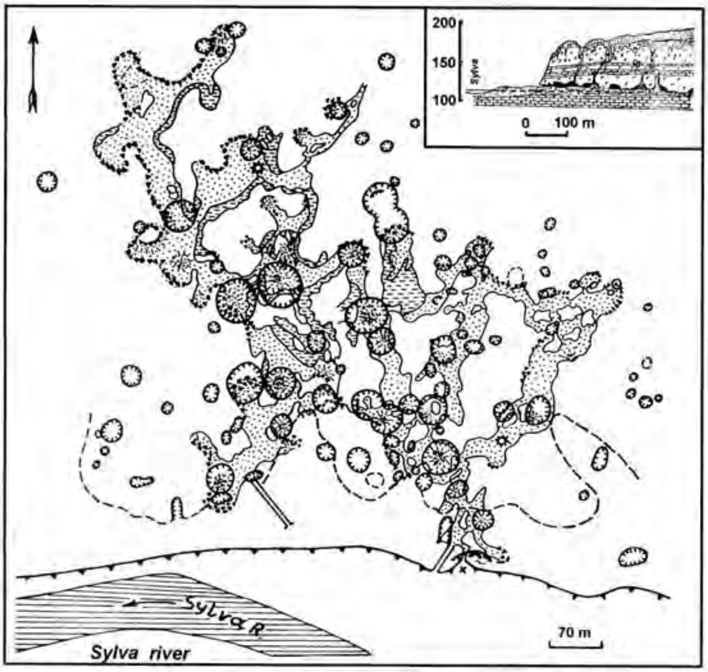

Fig. 1. Plan of Kungurskaya Cave in the Pre-Urals region, Russia, with breakdown features expressed at the surface as collapse and subsidence dolines.

below the gypsum due to intense uplift. In many of the maze cave systems there has been no significant widening of conduits due to dissolution at the water table, and simple breakdowns are uncommon. However, there are some exceptions, as exemplified by the Kryvsky quarry area in Bukovina, where during the Holocene the standing water table in the upper part of the gypsum bed was controlled by the nearby Prut river valley. This caused significant widening of conduits in the maze cave system (Zolushka Cave), and these have triggered many simple breakdowns that have propagated to the surface by upward stoping (Fig.2). Breakdown development was greatly enhanced by lowering of the water table in response to quarry operation (see Chapter I.10).

In entrenched karsts, where vadose conditions encompass all, or most, of a gypsum sequence, *vertical dissolution pipes* are a very common feature. They develop downwards from the gypsum's upper contact with a suitable protective layer (commonly limestone or dolomite), due to focused dissolution by groundwater that percolates through the overburden or leaks from an aquifer perched above the gypsum. Vertical pipes in gypsum have a diameter up to some meters. Relict lateral caves that pre-exist in gypsum sequences are commonly intersected by pipes as they cut down, even if the pipes are initially unrelated to the caves (for details see Chapter I.5). At some stage, dissolution pipe enlargement will induce breakdown of the overlying protective bed, leading to VTS development by the mechanism described above (Fig. 3). Ongoing downward percolation through such structures is vital to the upward stoping process. VTS of this type can propagate upwards through an overburden up to several tens of metres, ultimately reaching the surface while remaining disproportionately small in diameter (commonly 1 to 5m). In the Urals region (Dorofeev, 1970; Andrejchuk, Dorofeev & Lukin, 1990) and the Western Ukraine

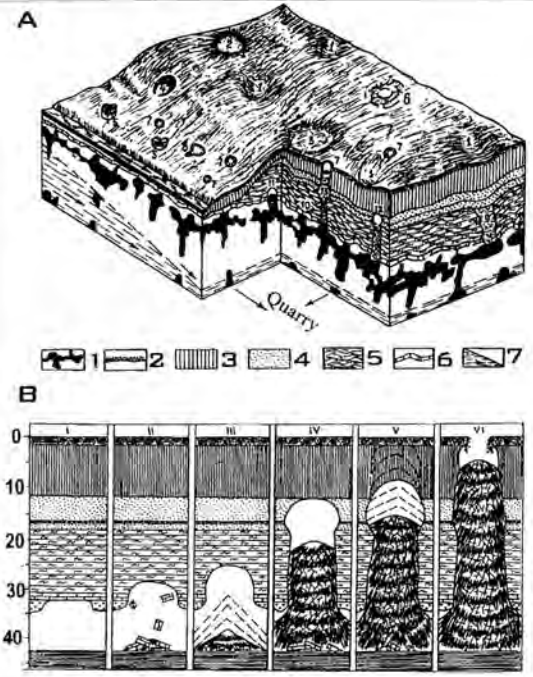

Fig. 2. Element of the karst landscape (A) in the vicinity of Kryvsky quarry above Zolushka Cave, Western Ukraine, and (B) the successive stages of breakdown formation (After Andrejchuk, 1991). 1 = cavities, 2 = soil, 3 = loam, 4 = sand, 5 = clay, 6 = limestone, 7 = water table drawdown cone. Numbers 1-13 on diagram A indicate various styles and genera of surface karst landforms induced by cave breakdown. Numbers I - VI on diagram B specify different stages of breakdown propagation at the surface.

(Klimchouk, 1984) it has been shown that most surface dolines in intrastratal entrenched karst settings evolve by means of the VTS mechanism being initiated by dissolution pipes in gypsum. A good example is shown in Fig.1, where most of the small- and medium-sized dolines above the cave are related to dissolution pipes in gypsum rather than to simple breakdown. VTS can easily be mapped in caves by observation of their characteristic breakdown talus piles, which contain sediments derived from the overburden and commonly show signs of continuing water percolation.

Dolines that evolve from VTS commonly become swallow-holes (ponors), transmitting some localized surface run-off underground. They support development of vadose caves, which are commonly represented by linear conduits. Such caves rarely achieve growth to significant volumes to give rise to breakdown that can propagate through the cover beds in entrenched karst. They normally develop a surface expression only at the denuded karst stage.

Structure of a gypsum bed or sequence. Single gypsum beds rarely exceed a few tens of metres in thickness, but gypsiferous sequences many tens to a few hundred metres thick are common, comprising gypsum beds intercalated with limestone, dolomite and/or other sediments.

Within a single gypsum bed, variations in rock structure and texture greatly influence the style of fissuring that is imposed by both lithogenetic and tectonic forces, thus helping to determine the potential structures of karst-generated voids. This aspect is discussed in detail by Klimchouk et al, 1995; see also Chapter I.1.

There is a great difference in the tolerance to cave breakdown exhibited by massive gypsum and layered (laminated) gypsum. The latter commonly contains clay as minor layers or impurities,

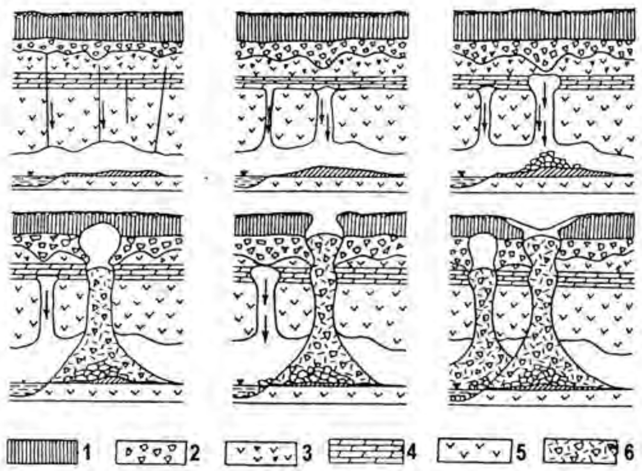

Fig.3. The successive stages of dissolution pipe development in gypsum, and VTS development in the overburden, with the final appearance of a doline at the surface (based on the example of Kungurskaya Cave). 1 = loams, 2 = breakdown slabs, 3 = gypsum, 4 = dolomite, 5 = gypsum-anhydrite, 6 = mixed breakdown clasts that form the body of the VTS and talus piles in the cave.

dramatically reducing the strength of the rock. Within some of the vast cave systems in the Western Ukraine there are zones where the host rock changes from the more common massive gypsum to thinly-bedded or laminated varieties. Such zones are especially prone to breakdown. In the Urals and adjacent regions, Permian sulphates have experienced a complicated history that included several major episodes of tectonic disturbance and karstification. As a result the gypsum here is closely fractured, or even brecciated, in places, and cave breakdown is much more common than in the younger (Miocene) and less broken gypsum succession of the Western Ukraine.

In the case of multiple sulphate sequences, it is of particular importance whether or not the other, intercalated, lithologies provide initial (pre-karst) aquifers. This factor can significantly influence the cave-generating flow architecture in an artesian system, in determining which gypsum horizons will be preferentially cavernous. This point is considered further below.

Structure, lithology and thickness of the overburden. The set of factors that includes the composition, structure and thickness of the sequence overlying a gypsum formation, is crucial both to the development of caves within a karstifiable unit and to mechanisms of breakdown formation and their propagation to the surface.

For cave development under confined conditions the hydro-stratigraphical aspect of whether a gypsum unit is surrounded below and above by aquifers or by low-permeability beds is important. This aspect is considered in the next sub-section below.

For VTS development in cover beds, regardless of whether an ascending or descending circulation operates, the presence of a fractured zone or major fissure that provides an initial path for cross-formational hydraulic communication is crucial.

In many areas gypsum sequences have some carbonate beds at the top, separating them from overlying poorly consolidated sediments such as clays, loams or sands. Such carbonate beds are important for the formation of vertical dissolution pipes, as they protect the evolving pipe from early infilling by unconsolidated sediments, and allow pipe growth to reach several metres in diameter. In this way a large enough void is created to trigger a VTS mechanism when initial break-

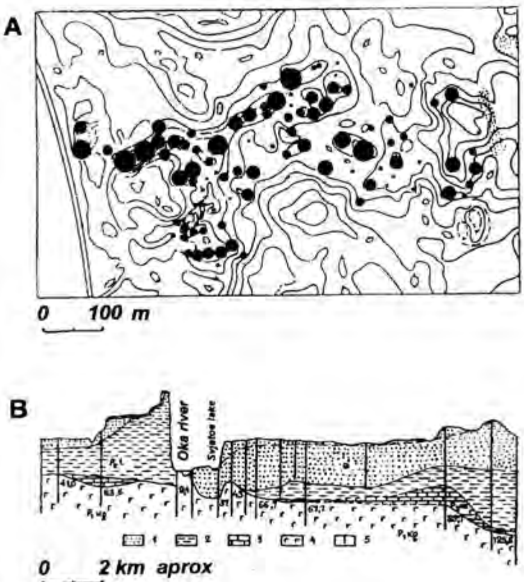

Fig. 4. A = Typical karst landscape near Dzerzhynsky city, Volga-Kamsky region, Russia. Recent dolines are indicated as black circles. B = geological profile through the area (After Karst Phenomena..., 1960).

down occurs.

Properties of sediments in the overlying sequence help to determine stoping mechanisms. In unconsolidated sandy materials VTS propagate rapidly and relatively uniformly in time. In loams, argillaceous sediments, clays and laminated shales stoping proceeds less uniformly (cyclic), and generally more slowly, by chip breakdown or small "block" breakdown. In cemented bedded rocks stoping occur during relatively long time spans, usually as block breakdown events. The shape and dimensions of the open space developed at the top of VTS can also vary between these lithologies.

Overburden composition (as well as hydrogeological activity within a VTS) determine the "void-transmissivity" of cover beds, i.e. their ability to transmit a void of given initial dimensions through a significant vertical extent of overburden. If the overburden consists largely of sandy sediments, even a relatively small breakdown cavity at the top of a karst unit may induce VTS propagation up to 80-100m upwards, providing the active groundwater circulation supports a suffosion (piping) process. When readily soluble rocks comprise a significant proportion of the overlying stratified sequence, and ascending artesian discharge occurs via VTS, the latter may extend upwards for up to 400-500m, as exemplified by cases in the Hebei Province of China (see Chapter II.13). If clayey sediments dominate in the overburden, VTS can normally reach the surface only where the overburden thickness is less than 45-60m. Where massive solid rocks overlie the gypsum, the VTS mechanism does not operate, except in cases where the massive cover beds consist largely of soluble rocks. For simple breakdown to achieve surface expression, large void volumes must be created within the gypsum, and the thickness of the cover beds must be relatively small. The void-transmissivity of cover beds determines a critical overburden thickness, above which intrastratal karst will receive no surface expression at all.

Fig.4 illustrates a typical surface karst landform assemblage in the Sredneje Povolzhje region, where Lower Permian gypsum occurs immediately below the floor of the Oka river valley. In most of the region it is overlain by Upper Permian porous carbonates and low permeability clays, but locally it is overlain directly by Quaternary fluvial sands (Karst phenomena..., 1960; see Fig. 4-B). Several generations of dolines are recognized. Recent dolines (shown as black circles) have formed most readily where the overburden comprises only sand, and they have evolved mainly where the thickness of sands is less than 80m.

The Western Ukraine presents a characteristic example of intrastratal gypsum karst (various sub-types), developed under a cover of predominantly clayey sediments. Argillaceous clays here vary in thickness from 5 to 100m or more. Karst landforms evolve when their thickness is less than 45-60m mainly due to the VTS mechanism, which starts after the roof of a vertical solution pipe has been breached. Detailed study and survey of breakdown talus piles through the maze of the Zolushka Cave system has allowed recognition of VTS that represent various stages of upward propagation (see Chapter I.10).

Examples of gypsum karst where a karstified unit is overlain mainly by (commonly soluble) solid rocks are numerous throughout many regions of Europe, Siberia and China. Settings of entrenched intrastratal karst with varying thicknesses of rocks above the intensely karstified horizon are represented in Fig. 5. The Ledjanaja Mount massif in the pre-Urals region is composed mainly by sulphates, with some carbonate beds (up to 3m thick), and a few metres of unconsolidated sediments at the top. The major river Sylva has incised to a depth of 70-90m. An intensely karstified horizon lies at, and immediately above, the present water table, some 60-80m below the surface of the massif, where Kungurskaya Cave is an explored part of the system (see Fig.1). The map below shows that the areas of highest density of surface karst features coincides with II-IV terraces, where the thickness of rock above the top of the karstified horizon does not exceed 25-40m. There is also a line of karst features at the edge of the plateau, along the steep escarpment that faces towards the river. In the latter case the dolines are related to suffosion processes induced by dissolution along unloading fissures. This is a common cause of high doline density along escarpment edges (see also karst trenches in sub-chapter 3 below). However, dolines also exist on the interior plateau areas, 60-80m above the "cave level". Detailed mapping on the surface and in the caves has proved that most such dolines have evolved via the VTS mechanism, after development of vertical dissolution pipes.

Hydrogeological conditions. Different types of caves that induce breakdown processes, are developed under a variety of hydrogeological conditions; these aspects are considered briefly above and, in more detail, in Chapters I.5 & I.6. For cave development under confined settings the most important criterion is whether a gypsum unit is immediately underlain and overlain by aquifers or by low permeability beds. In the latter case speleogenesis in gypsum might not advance until a unit has been exposed by denudation. If the gypsum is underlain by an aquifer but is overlain by low permeability rocks, cavities can develop mainly along the gypsum base, though some breakdown can be induced if large enough voids are created. The VTS mechanism can commence only where fracture zones exist, breaching the upper confining bed and providing paths for upward discharge from a particular aquifer. The most favourable configuration for speleogenetic

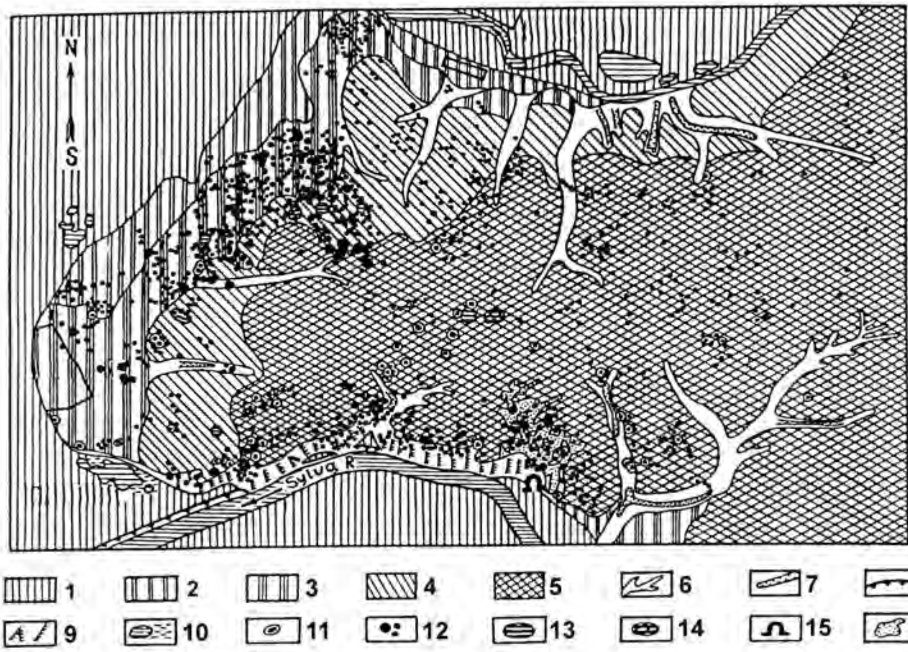

Fig. 5. Geomorphological map of the Ledja-naja Mount massif. 1-5 = terraces: 1 = I terrace (4-12m above the river), 2 = II terrace (15-25m), 3 = III terrace (30-40m), 4 = IV terrace (55-60m), 5 = higher terraces (>75m); 6 - 10 = erosional forms: 6 = ravines, 7 = steep-sided ravines, 8 = lip of the lowermost terrace, 9 = gypsum outcrops at the main escarpment of the Sylva valley, 10 = "mort" lakes; 11-16 = karst forms: 11 = cap-shaped dolines, 12 = cone-shaped dolines, 13 = lakes in dolines, 14 = swamps in dolines, 15 = caves, 16 = area of the Kungurskaya Cave.

development is where gypsum has aquifer beds below and above. Hydraulic communication through the gypsum bed (which acts initially as a low permeability bed) will be the main driving mechanism for cave development (for details see Chapter I.5). Depending upon the fissure structure within the gypsum, dissolution can be either uniformly dispersed or focused along sporadic fracture zones. Again, the VTS mechanism is only likely to start where fracture zones initially breach an upper low permeability bed that confines an aquifer system.

In complex stratified sequences, where a number of gypsum beds are intercalated with limestones, dolomites and clastic sediments, lithologies other than gypsum can provide lateral flow paths. Conditions similar to those already noted determine which gypsum beds will be preferred for cave formation. If the VTS development is triggered from a lower gypsum bed, then upward VTS propagation will be greatly facilitated by the fact that many of the infallen clasts, and the VTS walls, are composed of readily soluble gypsum from the upper beds.

Deep-seated (artesian) gypsum karst can achieve surface expression only via the VTS mechanism. This is possible where a significant hydraulic head gradients exists between a confined aquifer system comprising a karstifiable unit, and an upper unconfined aquifer. Yaoru & Cooper (Chapter

II.13) describe an active VTS that has propagated about 400m upwards from Ordovician gypsum in Hebei Province, China. Although this particular structure has not yet reached the surface, collapses known elsewhere in the area demonstrate such a possibility. When intersected by a coal mine at a depth of over 300m, this structure was discharging up to 12 m^3/s, flooding the mine with about 46km3 of water. A prominent example of large collapse dolines occupied by lakes was described by Quinlan (1967) in the Roswell area of New Mexico. The steep- to vertically-walled dolines, 50-100m wide, aligned along the Pecos valley, have formed in a zone of upward discharge from the Roswell aquifer, caused by collapses that were triggered by gypsum and salt dissolution at depths of several hundred metres. This VTS development was facilitated by the overburden of the Artesia Formation being composed of intercalated soluble and clastic rocks. Other impressive examples of VTS that discharge water from deep-seated confined aquifers, are know from the Urals foredeep.

Surface expression of subjacent intrastratal gypsum karst is more common, notably where gypsum lies at shallow enough depths to allow incision by major valleys to partially breach artesian confinement. A good example is the Sredneje Povolzhje region in the Russian Plain, where the Oka river has eroded a confining bed and deposited thick sands over the gypsum in some areas, while elsewhere the flow in the gypsum remains confined (see Fig.4-B). With overburden thicknesses varying from 10 to 130m, numerous dolines are forming at the surface, via the VTS mechanism, in areas where the gypsum lies at depths less than 80-90m. These VTS develop as upward circulation (discharge) paths.

Water table lowering within the upper aquifer, due to continuing valley incision, and particularly water table fluctuations within an unconsolidated overburden, result in activation of VTS development by suffosion processes.

When the entrenched karst stage is achieved, and the water table lowers below a cave horizon breakdown development is greatly accelerated due to removal of buoyant support. White (1988 estimated that limestone buoyancy in water contributes 40% of the ceiling support; a similar figu re for gypsum is about 44%. Removal of buoyant support is commonly followed by a stage c intense dissolutional widening of passages and erosion of cave sediments (including breakdow talus piles) due to water table and backflooding water activity. Thus, this stage is highly effective terms both of triggering/VTS development new breakdown and activating pre-existing, but st "hidden", VTS. In other words, these hydrogeological conditions are most favourable for suppo ting collapse and subsidence formation at the surface. In gypsum karst areas where these con tions are active now, the rate of recent collapse occurrences can be as high as several collapse a year per km^2.

Under vadose conditions, breakdowns in relict caves are commonly stabilized. Previously formed VTS may continue to develop (upward stoping) if they drain perched aquifers within the overburden. New VTS originate only along vertical dissolution pipes, which develop readily where leakage paths in cover beds allow water to reach the top of a gypsum stratum (see Fig. 3). Continuing downward percolation through such structures is vital to the progress of upward stoping. This view is supported by observations that all successive perched aquifers in a stratified sequence, and eventually the uppermost aquifer, will leak into a VTS, dissolving soluble infallen clasts and washing out unconsolidated material, creating voids within the structure and allowing further stoping to occur.

Most maze caves in the Western Ukraine contain numerous pipes superimposed upon relict passages, as the upper aquifer is normally within Quaternary sediments, perched on thick clays within intervalley massifs. This aquifer drains mainly downslope, but leakage occurs along tectonically weakened zones through the clays, giving rise to dissolution pipes in the gypsum. However, some caves contain no vertical pipes at all, because they lie beneath areas that lack an upper aquifer, where no porous sediment is present above the clays.

3. Superficial features of intrastratal karst

Superficial features of intrastratal gypsum karst display many similarities, but also some diffe-rences, to carbonate karst. The most important characteristic of intrastratal karst, common to all ithological karst types, is that superficial forms evolve almost exclusively as a reflection of pre-exi-ting underground karst features.

)issolutional sculpting micro- and meso-forms. A wide variety of dissolutionally sculp-ed karst landforms, such as different karren types occurs in intrastratal karst, but only on very mited areas of rocks that crop out locally along valley slopes and escarpments or in collapse doli-es. They are discussed in Chapter I.9.

)olines. Dolines are by far the most common superficial feature of intrastratal gypsum karst. hey evolve as collapse or subsidence forms. Their shape and size when they first appear depends ıainly upon the type of initial breakdown in the gypsum and on the thickness and composition of ıe overlying cover beds.

VTS that develop from deep-seated karst appear on the surface mainly as collapse dolines. The ›llapse is commonly catastrophic. Many such dolines have a pit-like (cylindrical) shape and preciable size (diameters and depths of 40-50m are common, and locally they can be larger ll). This is because VTS in deep-seated karst can propagate successfully through many tens or veral hundred metres of overburden only if they develop along large tectonic fracture zones, d if groundwater circulation is sufficiently active to support creation of additional voids.

When a karst horizon lies at relatively shallow depths, increasingly diverse shapes and sizes of d ines appear. Vertical lithological heterogeneity in the upper part of cover beds determines how V affect the surface. If denser or better-consolidated deposits lie at the top, above sandy sedi-m ts, sudden collapse dolines are more likely to appear. Newly-formed features are commonly cy drical (pit-like), pitcher-like, or bowl-like in shape. Similar shapes result where cover beds are ela ic and collapse en masse. Where sandy sediments or light loams cap a succession, dolines ten to evolve by gentle subsidence or as smoothly-shaped collapse forms, although cone-shaped on are also common if suffosion processes operate. The latter shapes are also typical within oth poorly consolidated lithologies if active ponors open up at the bottom of dolines. Regardless of the initial doline shape formed in loose sediments, they tend to grade towards smoother profiles quickly, in spans of only months or a few years, except where well consolidated rocks cap a sequence or where suffosion and active ponors operate. Gorbunova (1979) described two remarkable examples of the rapid evolution of recent dolines. The Brekhovsky collapse in the Perm region appeared in 1953 as a 40m-deep shaft. In 1954 its depth was 28m and its diameter was about 25m at the surface and 3 to 5m near the bottom. In 1961 it was a bowl-shaped doline about 30m in diameter and only 15m in depth. The other example is from the Angara region in Siberia, where a 56m-deep collapse shaft half-filled with water appeared suddenly in 1949. Its upper diameter was only about 4m, but the shaft had a pitcher-like shape. In 1951 it was a pit 15m deep, and by 1957 the form had turned into a doline 15m in diameter and 16m deep.

With increased variation in cave formation and changing hydrogeological conditions from artesian through phreatic and water table to vadose, the full range of possible VTS triggering and development mechanisms is realised. Finally, when a thickness of cover beds is lowered sufficiently within a particular geomechanical setting, simple breakdowns can also evolve into collapse dolines, and purely suffosion features can form by cover sediments being washed into open fissures at the top of a karst unit.

An example of a deeply entrenched intrastratal karst landscape, where the cover is relatively thick and largely impermeable, is provided by the Podol'sky sub-region in the Western Ukraine. Maze caves here are relict, having developed under earlier artesian conditions, and there are no large voids to trigger significant breakdown. Major valleys have entrenched deeply below the gypsum, but thick clay cover remains largely intact within wide intervalley massifs. Dolines commonly evolve in response to VTS stoping, or as sporadic simple breakdowns, in the floors of minor perched valleys that approach the gypsum. They become ponors that intercept the surface run-off, so the valleys become dry and commonly separated into several closed basins. Outside such valleys, dolines form almost exclusively due to VTS stoping. Doline density in the area is commonly relatively low, though it increases dramatically where erosion has removed most of the overburden, as for instance on the extensive upper terraces of the major rivers.

A typical example of an entrenched karst landscape with thin and permeable cover is illustrated in Fig. 6. Dolines here have evolved through different mechanisms: as simple cave breakdowns, as VTS, and as suffosion features. Older dolines are fossilized and stabilized. Some dolines are rejuvenated, and new forms appear commonly superimposed upon the older features. The resulting doline fields are polygenetic and may became very complex. Dolines can cover up to 30% of the total area.

A still more diverse karst landscape is observed in some areas of the Pinego-Severodvinsky karst region, where the thickness of permeable cover beds above the Permian gypsum is relatively low (ranging from few metres to a few tens of metres). Major rivers have incised only slightly below the Permian gypsum and many tributaries operate within the gypsum horizon. Large cave passages have developed during this stage, transmitting significantly large active streams, perched upon the underlying non-karstifiable bed. Many of the trunk passages have been partially destroyed by collapses, which have produced an intermittent karst hydrology, dry karst valleys and canyons, bridges, and so on (Caves..., 1974). Vertical dissolution pipes are common, being formed beneath thin unconsolidated sediments and a minor bed of dolomite at the top of gypsum. This bed collapses readily, and the pipes become pits. There are some areas where the density of such pits is many hundreds per km^2. Being complicated by superimposition of larger

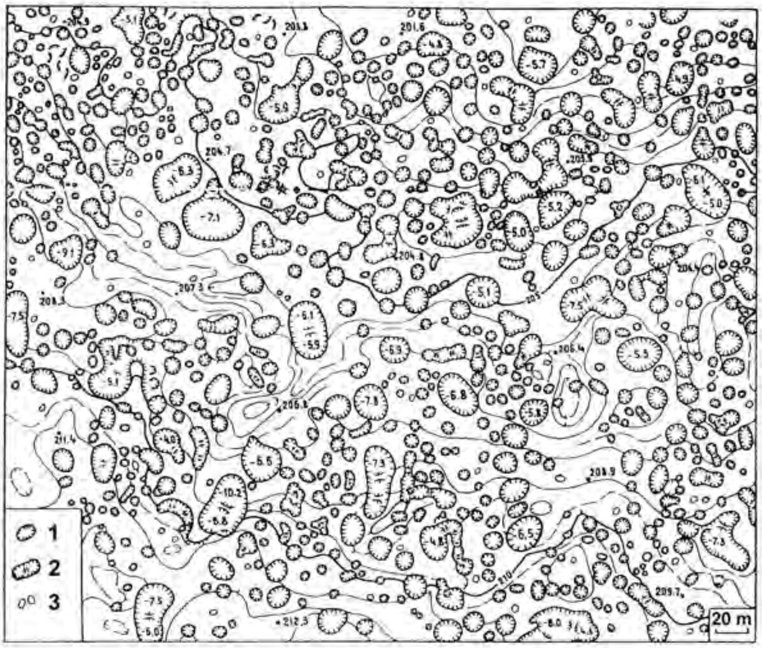

Fig. 6. Typical landscape of a gypsum karst area in the Iren river basin, Pre-Urals, Russia.

collapses formed in response to cave breakdowns, such areas represent a kind of "karst badland", known locally as "shelopnjak". This karst landscape has almost passed into the category of denuded karst.

Data describing the parameters of about 2800 dolines in intrastratal gypsum karsts have been summarized by Gorbunova (1979). Fig. 7 illustrates the frequency distribution of dolines according to their diameter (A) and depth (B) . Most of the dolines have a diameter between 5 - 25m (10-15m is the most typical diameter) and depths ranging between 1-3m. However, it must be noted that the data set includes measurements reflecting a variety of cover bed thicknesses and compositions, though overall the area can be viewed as an entrenched karst.

Other important surface karstification characteristics are the density of dolines (expressed as number per km2), index of surface karstification (expressed as the ratio of area of dolines to total area, %), and rate of doline appearance (expressed as the number of new dolines appearing per year per km^2). These parameters are meaningful if determined for limited areas that are characterized by a relatively homogenous distribution of karst forms. They have been utilized widely for local karstological mapping and engineering-geological assessment of gypsum karst terrains in the Soviet Union (Savarensky, 1967; Iljin, Savarensky & Tolmachev, 1972; Tolmachev, Troitsky & Khomenko, 1986). Characteristic figures for intrastratal gypsum karsts vary, for density, from a few tens to a few hundred dolines/km^2, for index of surface karstification - from a few to a few tens percent, for the rate of appearance - from 0.01 to 3.0 dolines per year per km^2 (Gorbunova, 1979). However, anthropogenic impact may increase the values for the latter characteristic dramatically (see Chapter I.11).

Some studies suggest that collapse and subsidence processes are activated during specific

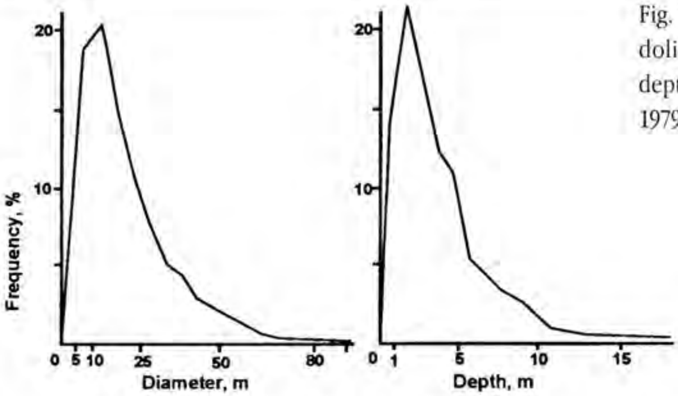

Fig. 7. Frequency distribution of dolines by diameter (left) and depth (right) (After Gorbunova, 1979).

periods. In the Kungur area of the Pre-Urals, new collapses occur most frequently in years with the highest precipitation and spring floods (Lukin & Ezhov, 1975). In the Volga region of the Russian Plain, collapses commonly coincide with periods of minimal levels in the Volga river, when it increasingly drains underground waters (Kaveev, 1967). Andrejchuk (1984) found that in the Bukovinsky sub-region of the Western Ukraine collapses occur predominantly during extremely dry or extremely wet periods. For the Bashkiria region in Russia, a cyclicity of some 11-16 years is revealed in the activation of collapses, related to climatic and karst water regime factors (Gorbunova, 1979).

In exposed gypsum karst areas (the sub-types of denuded and, particularly, barren karst) solution dolines are much more common than the collapse and subsidence features considered above. However, there may be great differences between the individual karst landscapes that represent the exposed karst type. Such differences are partially related to the various structural and geomorphic settings of exposed gypsum sequences, but probably the most important are evolutionary differences between denuded and barren karst sub-types. As defined in Chapter I.4, denuded karst is a former intrastratal karst, that has inherited structures from sub-surface karstification, whereas barren karst represents a system that has evolved largely in adjustment with the exposed geomorphic setting. Dissolutional landforms found in exposed karsts are discussed in chapters I.8 and I.9 of this volume.

Karst trenches. These typical intrastratal entrenched karst features are known from many parts of Russia, Germany and Canada. Karst trenches develop along escarpment edges and on the upper parts of steep slopes where gypsum crops out. They are markedly elongated closed depressions with irregular floors, commonly complicated by ponors and small dolines. The characteristics and mode of genesis of trenches in gypsum karst terrains have been summarized by Gorbunova (1979). Trenches vary considerably in size: from a few to 250-200m in width, from 10 to 2500m in length, from a few to 20m in depth. They form along clefts and fissures that originated due to unloading of a massif towards a side that has been opened up by erosion or other geomorphic processes. Unloading commonly enlarges pre-existing tectonic fissures. Some larger clefts can open directly to the surface and then further widened by gypsum dissolution. More commonly, extensive fissures form and then enlarge by dissolution under a still-continuous and

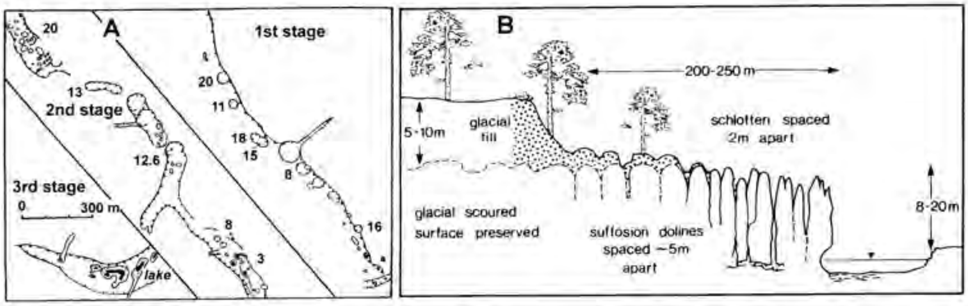

Fig. 8. A = The development of karst trenches in the Polazna area, Pre-Urals, Russia (After Butyrina, 1962). Stages are explained in the main text. Numbers indicate the depth of dolines. B = Progressive development of shlotten topography in massive gypsum near Windsor, Nova Scotia, Canada (After Ford & Williams, 1989).

poorly consolidated cover, until trenches develop in response to doline evolution (Butyrina, 1962; Lukin, 1966). Features representing different stages of such evolution (Fig.8-A) are also described under the term "shlotten depressions" or "shlotten karren" (Ford & Williams, 1989; Kempe, Chapter II.5). The first stage involves formation of separate dolines along a fissure, by suffosion and breakdown. During the second stage adjacent dolines amalgamate into a trench. Within the third stage the trench floor is smoothed and can be filled with poorly permeable alluvial deposits, allowing the formation of lakes, or a trench can be breached to one side. Several trenches can combine. Small caves are commonly associated with trenches, especially during the first development stage. Broken edges of exposed gypsum karst massifs and ridges, with deep clefts and displaced large gypsum blocks, are quite typical of some parts of Italy and Spain. In such cases dolines and trenches do not form (due to the lack of cover sediments), but the features provide clear illustrations of the unloading/gravitational phenomena that initiate development of the features described above in intrastratal karst settings.

Karst valleys. Minor stream valleys perched on a non-karstifiable cover commonly become dry and then separated into several discrete closed basins as evolving dolines and ponors pirate surface flow. A valley can be terminated by development of a single large ponor, or a group of sink points, at its downstream end. Development of such valleys in the exposed karst type is considered in Chapter I.9. Karst valleys of different sizes (up to a few kilometres in length) are very widespread in many regions of intrastratal entrenched karst (e.g. in the Western Ukraine, the Belomorsko-Kulojsky Plateau, the Volga region, the Pre-Urals and the Urals). Further incision into the gypsum commonly leads to a total breakdown of cave passages beneath a valley, so that valleys may become complicated by breakdown canyons (as for instance in the Angara region, Siberia). Canyons formed due to the destruction of cave passage roofs are also known from exposed karst areas (e.g. Sorbas in southern Spain). In areas where notable caves with underground streams existed, their breaching may result in development of a valley that inherits the course of a trunk cave passage, having been further widened after breakdown. The stream effectively becomes a surface one, although it may appear from a cave at its upstream end and disappear into a cave at its downstream end. The Karjal valley on the Belomorsko-Kulojsky Plateau is an example of this type, about 10km long, 10 to 100m wide and up to 30m deep. It has five known caves at its upstream end, and steep gypsum outcrops along its walls. The valley floor is perched on a dolomite bed that underlies the gypsum. Karst valleys of another type, also known in this region, developed by a cliff above a large cave passage, retreating backwards from a major valley toward the interior of a plateau. Such valleys are typically 300-400m long (locally up to 1km) and 20-50m deep (Saburov, 1974).

Karst depressions. Depressions (forms that are larger than common dolines) in areas of intrastratal gypsum karst have different, commonly complex, origins and dimensions. In the most general terms, depressions represent some of the latest stages in the development of gypsum karst.

Relatively small depressions, 100-500m wide and a few tens of metres deep, form by overenlargement of a single doline or by the fusion of several dolines. Intensely karstified areas with a high density of normal dolines can eventually evolve into depressions. In areas of temperate climate, such depressions commonly become partially filled with poorly permeable sediments, and may be occupied by lakes.

Intermediate depressions, a few to several tens of kilometres in lateral extent, commonly result from the fusion of several smaller depressions or from enlargement of karst valleys. In some respects many of these can be considered as analogous to the poljes of carbonate karsts (Gorbunova, 1979). Depending upon relationships with non-karstifiable rocks, structural and hydrogeological settings, gypsum karst analogies can be drawn with three major polje types: border, structural and baselevel poljes (Ford & Williams, 1989). Generally They may have surface flow across their floors, eventually sinking at ponors, or contain lakes that represent "windows" into the water table. Different kinds of intermediate depressions within the intrastratal karst types are widespread in the Belomorsko-Kulojsky and Pre-Urals regions of Russia. The most favourable are zones for their development are on the sides of large positive tectonic structures, where sulphates are in lateral contact with carbonate or terrigenous rocks (Gorbunova, 1979).

Large depressions, up to a few hundred kilometres in lateral extent are known in Canada, New Mexico, Texas and Russia (Ford & Williams, 1989). The term "solution subsidence troughs", also applied to such depressions, can be confusing, as it implies a gradual lowering of the surface. In fact, such depressions are commonly developed in structural situations like that mentioned above, or at the margins of large gypsum and/or salt deposits, by slow retreat of the dissolution front, with the "belt" of the karst landscape slowly shifting in the direction of retreat. The final results of intrastratal karst development within the belt are a karst breccia that replaces the karstified horizons, and a lowered surface that follows the migration of the belt. Within the karst belt the lowered surface is the result of the complex evolution and lateral migration of karst features rather then of uniform subsidence. Such depressions may have no (or only slight) topographical expression, as they are commonly infilled by terrigenous or other sediments, this being the reason that Quinlan (1978) termed them "solution-induced basins". Large depressions of this type develop during geologically lengthy time spans and are considered as palaeokarst features (Ford & Williams, 1989).

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Chapter I.11

ENVIRONMENTAL PROBLEMS IN GYPSUM KARST TERRAINS

Alexander Klimchouk & Vjacheslav Andrejchuk

Introduction

Karst terrains are inherently vulnerable, as they are characterized by highly inhomogeneous permeabilities, complex underground drainage systems, the ability to transmit fluids and pollutants easily, and a susceptibility to surface collapse and subsidence. Karst areas commonly pose numerous and severe environmental problems and hazards. Human practices and management procedures, developed for most normal terrains, may enhance these problems dramatically when applied to karst terrains.

Over the past few decades the specific and fragile nature of karst systems has become increasingly well understood scientifically, and much attention has been focused upon the methodology and practices of karst resource protection and hazard assessment. However, the vast majority of studies have been focused specifically upon carbonate karst. The exception was in the former Soviet Union, where the extensive area covered by gypsum karst, and its associated severe problems (commonly enhanced by bad management practices), forced investigators to pay particular attention to the special characteristics of gypsum karst terrains. The last decade, however, has been marked by an explosive increase in interest specifically in gypsum karst, driven by the needs of expanding and "deepening" economic activities, in many countries throughout Europe, North America and Asia, particularly in Germany, England, France, Spain, the United States and Canada.

Environmental problems and hazards induced by gypsum karst have been more clearly recognized by engineering geologists than by karstologists. The reasons are twofold: 1) there has been a generally poor recognition of gypsum karst as a "true" karst among mainstream karstologists (see Chapter I.4) and, 2) compared to carbonate karst, areas of exposed gypsum karst are small, and the wide development of deep-seated intrastratal gypsum karst has been poorly appreciated within the predominant "geomorphological" paradigm of karstology. Engineering geologists commonly deal with gypsum karst hazards. However, they tend to treat such hazards as local dissolution or "leaching" effects, without recognizing the full nature and structure of karst systems, the principles of their evolution and their detailed behavior.

Most of the environmental problems and hazards characteristic of carbonate karst are also found commonly gypsum karst terrains. However, the more rapid dynamics of gypsum karstification and some of the geological peculiarities of evaporitic rock formations result in associated problems and hazards commonly being even more severe than their equivalents in carbonate karsts. Gypsum karst is also much more susceptible to human impacts, particularly if changes in groundwater circulation are induced.

The present paper is not intended to provide a comprehensive consideration of all recorded environmental problems associated with gypsum karst. In order to draw attention towards specific areas of concern, it concentrates upon noting some of the effects related to human impacts that are unique to karst systems in gypsum or most commonly occurring, and reviews some representative examples.

1. Some characteristics specific to gypsum karst systems

The main differences between karst development in gypsum and in carbonate rocks lie in their dissolution chemistry and kinetics, and in various geological peculiarities of the respective rocks and formations. Solubility and dissolution rates of gypsum are much greater than those of carbonates. Under suitable hydrogeological conditions, substantial dissolutional growth of conduits and cavities can take place within a few years in gypsum, while in carbonate karst rates of void enlargement can rarely achieve significance within the human life or construction industry time scales. From the civil engineering viewpoint, gypsum is by far the most problematical of the naturally occurring foundation materials. It has been pointed out (James, 1992, p.235). that gypsum "...has an 'awkward' solubility; neither so high as to be easily washed from surface deposits nor so low as to be unaffected in foundations".

Carbonate and gypsum karsts both occur most commonly in intrastratal settings, where karstifiable units lie beneath some thickness of cover beds, which may be poorly consolidated. From the point of view of many human practices, such settings can present more problems then are presented by exposed karst settings. Also, intrastratal karst terrains are, in general, much more heavily populated and industrialized than are areas of exposed karst, and this imposes far greater human impacts. Against this background, intrastratal gypsum karst terrains are less stable, more prone to subsidence and collapse phenomena and more vulnerable to changes induced by human activities, than are analogous regions of carbonate karst. Examples of the dramatic acceleration of karst processes in a response to anthropogenic changes, with consequently catastrophic results, are numerous in gypsum karst regions. A final factor that should not be overlooked is that the depth at which intrastratal karstification can affect the surface through collapse is generally far greater in gypsum karst than in carbonate karst terrains.

2. Water resources

Resources of underground water associated with gypsiferous formations are commonly quite large, although their use is relatively limited because their quality is only fair to poor due to their high content of sulphates. Substantial sulphates concentrations are also generally present in waters stored within adjacent aquifers that are connected hydraulically to gypsiferous aquifers. Waters in gypsum karst terrains commonly contain over 1,000 mg/L (locally more than 2,000 mg/L) of sulphates, which makes them unsuitable for use as domestic water supplies. Much higher concentrations are not uncommon where gypsum karstification is accompanied by dissolution of the various other salts that are associated with evaporitic sedimentary formations. However, underground water sources are exploited widely for industrial and agricultural needs in many areas where other water resources are scarce. This practice is commonplace in many parts of the USA (including Oklahoma, Texas and New Mexico), Spain, Germany, the Baltic Republics, the Western Ukraine, Russia, Libya, Iraq, China and elsewhere.

3. Pollution

Gypsum karst systems are susceptible to pollution in much the same way as carbonate karst, especially in situations that include superficial recharge. This is a reflection of commonly well-developed point recharge systems (especially characteristic of intrastratal karst), reduced self-purification capabilities and rapid rates of conduit flow. There are few aspects relating to the pollution susceptibility of gypsum karst that are not also applicable to carbonate karst. Several examples of different kinds of pollution documented in typical gypsum karst areas are described below.

3.1. Pollution by oil

In the Kungursky area of the Pre-Urals (Russia) oil is produced from the thick Artinsky limestone sequence, which is overlain by evaporitic (gypsum, anhydrite and dolomite) and terrigenous (sandstone and argillite) rocks. In the course of production, transportation and processing, spillage is common due to poor technological standards and management. During such accidents, large quantities of oil have been spilled into dolines with ponors; sometimes this has been done intentionally, in order to "reduce" the visually impact of the losses. Some dolines with plugged, or partially plugged, bottoms became oil lakes, and the karst aquifer can become severely polluted by oil. Areas of polluted groundwater (including karstic groundwaters - within areas of gypsum karst) are shown in Fig.1.

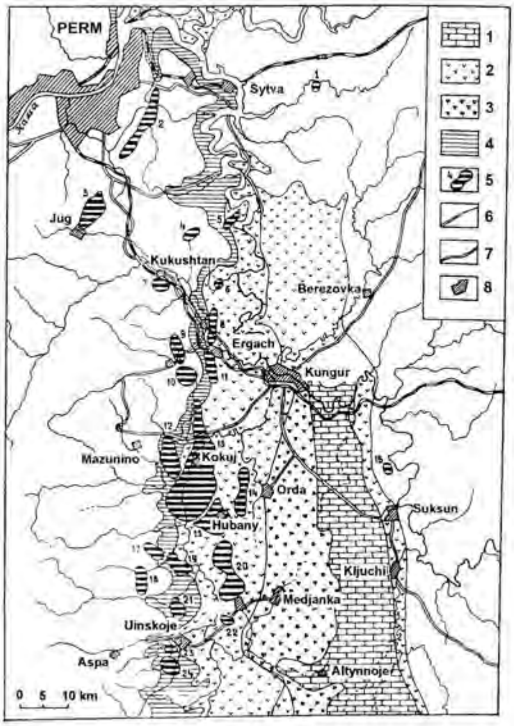

Fig. 1. Areas of oil pollution in the karst areas of the Pre-Urals. Areas:
1 = of carbonate karst,
2 = of denuded gypsum karst,
3 = of karst breccias,
4 = of intrastratal entrenched and subjacent gypsum karst,
5 = of groundwaters polluted by oil;
6 = roads,
7 = railroads,
8 = settlements.

Well-developed karst permeability and the physical and chemical characteristics of the pollutant determine a very slow rate of self-purification of the groundwaters. In "favourable" conditions oil has accumulated in karst reservoirs in such quantities that the possibility of developing such "secondary" oil reserves has been put under evaluation. The problem of pollution of karst waters by oil is of regional extent in the Pre-Ural region.

3.2. Radioactive pollution

After the Chernobyl accident radioactive fallout produced a pattern of pollution in some localized areas, even at a significant distance from Chernobyl. One such polluted "island" is an area in the north-west of the Chernovitsky region in the Western Ukraine, some 500km from Chernobyl. Levels of radioactive pollution at the surface remain as high as 30-40 μR/h, even 10 years after the accident. Study of the distribution of radioactivity has revealed that the local presence of karst landscapes is one of the major factors controlling the differentiation of radioactive pollution through the area.

Accumulation of radionucleides is favoured by a high content of carbonates and organic matter in soils. Relief plays an important role, causing radionucleides to be washed high ground and transported towards relatively lower points, particularly into dolines. However, dolines accumulate radionucleides only if their bottoms are plugged by loose material (Fig. 2-B). Radioactivity levels increase from doline edges to their floors, where they reach the maximum values recorded for the area (60-70 μR/h). At the lips and on the slopes of dolines the radioactivity levels are lower (20-25

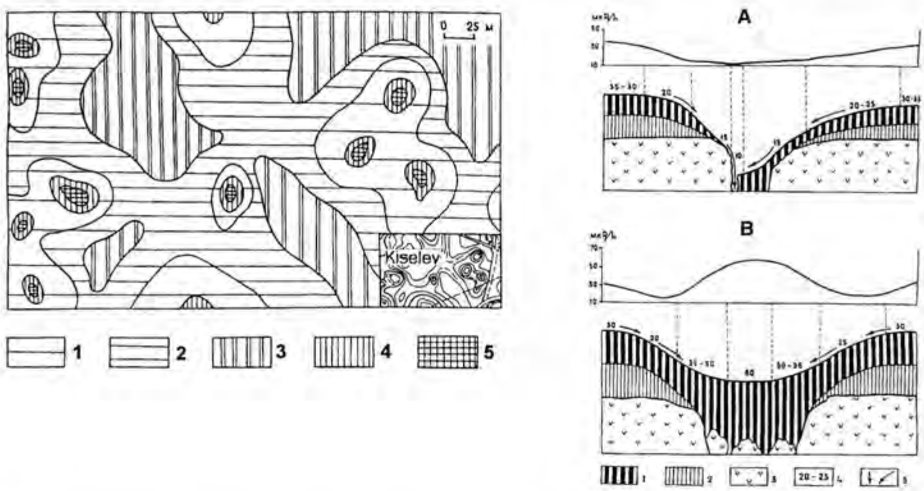

Fig.2. Distribution of radioactive pollution through an area of gypsum karst in the Western Ukraine. Left: part of the map of surface radioactivity. Values in μR/h: 1 = 21-25, 2 = 26-30, 3 = 31-35, 4 = 36-50, 5 = 51-65. Right: characteristic distribution of surface radioactivity across dolines: A = with an open ponor, B = with plugged bottom. 1 = soil, 2 = loam and clay, 3 = gypsum, 4 = radioactivity levels (μR/h), 5 = surface runoff.

μR/h) than the regional background. In contrast, dolines that contain sink points (ponors) demonstrate the lowest values at their bases (Fig.2-A), 10-20 μR/h, which is comparable with the regional background levels before the Chernobyl accident. Distribution of radioactivity throughout the area reflects the action of these two mechanisms (Fig.2-left).

3.3. Pollution by fertilizers

Many regions of intrastratal gypsum karst throughout Germany, the Baltic Republics, Ukraine, Russia and other countries are dominantly agricultural. Wide and locally intensive use of agricultural chemicals leads to pollution of karst waters by organic and mineral fertilizers and pesticides. Heavy pollution of a gypsum karst aquifer by nitrogen and organic compounds in Lithuania and Latvia is reported by Paukstys & Narbutas (Chapter II.10). Significant concentrations of pesticides have been measured in the waters of cave lakes, and in clay fillings, in Optimisticheskaja, Ozernaja and Zolushka caves in the Western Ukraine (Andrajchuk & Klimchouk, 1993). In the Western Ukraine pollution of karst aquifers by fertilizers is commonly enhanced by the effects of land reclamation measures (soil water drainage), where many soil drainage pipes are routed into dolines with sinking ponors.

4. Mining activity

Gypsum karst has a considerable influence upon the conditions of mining operations and, in turn, mining commonly produces a strong impact on gypsum karst.

Gypsum itself is a commodity that is mined heavily in many countries (including Russia, Ukraine, China, Germany, Canada, USA, Spain, Italy and France). Gypsum mines, whether open-cut or underground, produce generally localized impacts if the operation takes place in the unsaturated zone and does is not accompanied by underground water abstraction. However, even in these cases, considerable damage to landscape characteristics and cave resources can occur (as has happened in Germany, Italy and Spain). If water abstraction is involved, the impact can be much more complex and severe, as illustrated by examples from the Western Ukraine. The latter problems are discussed below.

A widespread problem associated with gypsum mining operations is that gypsum beds are commonly assumed to be aquifuges. This assumption seemingly allows the possibility of safe mining, even below base level. However, the possibility of rapid dissolutional enlargement of underground flow paths is frequently underestimated. Flooding experienced at the Izhemsky gypsum mine in the Timansky region of Russia clearly illustrates the relevant dangers (Lysenin & Sosnovskaja, 1974). Underground workings in Devonian gypsum were some 20-35m below the water level in the nearby Izhma river. At the initial stage of the operation water inflows into the workings were negligible, but they reached 1,700m^3/day in 1959 and increased to 20,000m^3/day in 1965. This inflow developed due to piracy of water from the surface river and eventually necessitated abandonment of the mine. Numerous collapses formed at the surface between the mine area and river during the last few years of the operation and its associated intense water abstraction. The total water withdrawal in 1961-1965 amounted to 8,820,000m^3, and the related dissolutional removal of gypsum was estimated at 11,500 tons or 5,000m^3.

Some commonly mined mineral commodities (such as salts) are found associated with evaporite formations, or with gypsum that has formed due to epigenetic processes (such as native sulphur). Extraction of salt by the underground leaching method commonly induces collapse and subsidence processes in the overlying gypsiferous strata, disrupting their integrity and greatly enhancing gypsum karst development. Such cases are known from the Donetzk region in the Ukraine and the pre-Caspian region in Russia. Epigenetic sulphur deposits associated with gypsum are most extensively mined in the pre-Carpathian region of the Western Ukraine and Poland, and in New Mexico and Texas in the United States.

Finally, mining of various materials that occur in the strata that overlie or underlie gypsiferous formations can be severely complicated by the presence of gypsum karst and can commonly result in its activation. In the Western Ukraine, clays overlying the gypsum bed are mined for the cement industry. This activity is greatly complicated by the subsequent activation of karst processes in the confined gypsum aquifer below, resulting in massive inrushes of water, and collapses. In the Shanxi coalfield of China, mining is severely complicated by the presence of vertical through structures (VTS; see Chapter I.10 for discussion of their general characteristics) that are related to gypsum karst in the deep-seated Ordovician Fengfeng Formation (Yaoru & Cooper, 1997; Chapter II.14 in this volume). The VTS serve either as conduits, allowing surface and overlying groundwater to enter the mine workings, or as paths along which underlying confined carbonate aquifers can discharge upwards. Some of the largest inrushes of water recorded in Chinese mines were related to the latter situation. For example, a VTS intercepted by a mine at the depth over 300m discharged up to $12m^3/s$ to flood the mine, yielding about $46km^3$ of water (Chapter II.13).

In all cases, backward and forward impacts between mining operations and gypsum karst are at their greatest where the mining has a significant effect upon the architecture of underground water circulation, and is accompanied by water abstraction. This issue is discussed further below.

5. Underground water abstraction

Abstraction of groundwater from gypsum karst aquifers, or from aquifers adjacent to them, for water supply, or during the course of mining operations, commonly causes a very marked impact on karst development in gypsum. Increased hydraulic gradients determine an increase in flow velocities and dissolution rates, which can sometimes result in a dramatic intensification of karst processes. Well-documented examples from the Western Ukraine illustrate the possible consequences.

Owing to differential uplift during the Late Pliocene to Pleistocene and the consequent deep incision of major valleys, the current settings of karst development vary between three sub-parallel zones. These represent respectively the deep-seated (confined), subjacent and entrenched subtypes of intrastratal karst (see Chapter II.9 for details). Within the zone of entrenched karst the gypsum is fully drained and quarrying does not create many problems.

The Kryvsky gypsum quarry lies on the border between Moldova and the Ukraine, in an area where, during the pre-quarrying period, the water table was established within the upper part of a 30m-thick gypsum bed, just 1-2m below its upper surface (subjacent karst setting). The gypsum

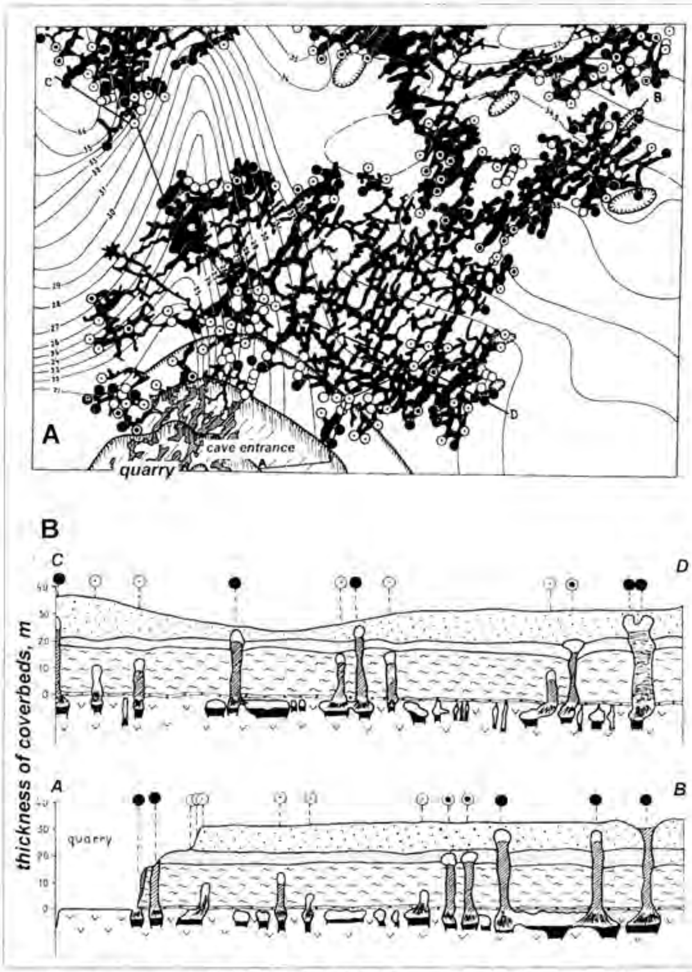

Fig. 3. Distribution of breakdowns (VTS) within the area of Zolushka Cave in the vicinity of Kryvsky quarry, Western Ukraine (After Andrejchuk & Klimchouk, 1993). A = plan, B = profiles. Circles of different styles indicate various stages of upward propagation of VTS.

aquifer is connected hydraulically with an underlying sandy-carbonate aquifer. Forty-years of quarrying and associated water abstraction have led to a 15-25m lowering of the water table, resulting in that the upper storey of a huge maze cave system becoming accessible (Zolushka Cave; 92km of passages are surveyed to date). The drawdown cone in the potentiometric surface has expanded to cover an area of 400km^2. There is also a lower storey to the cave, still water-filled, and connected to the upper level by vertical pits.

De-watering of the cave system has been accompanied by drastic changes of hydrochemical conditions within the aquifer, resulting in deposition of large quantities of iron and manganese hydroxides (Volkov et al., 1987; Andrajchouk & Klimchouk, 1993). Also, desiccation of clay fill in the cave and continuing water circulation at lower level have caused a reduction in the volume of cave sediments and triggered many subsidences inside the cave. Previously formed breakdowns have been re-activated due to subsidence of underlying material. Vertical solution pipes have developed in the extended vadose zone, causing new breakdowns to take place due to upward stoping (see Chapter I.10). The distribution of breakdowns throughout the cave area in the vicinity of the quarry is shown in Fig. 3. Survey of the breakdown talus in the cave has allowed its classification according to age, relative to the start of quarry operations. Of a total of 405 breakdowns, 24.4% are classified as natural and pre-technological, 16.3% as pre-technological but re-activated during the modern stage, and 60.3% are entirely recent, having formed in the last 35-40 years of quarry operation.

Even more severe consequences, in terms of underground water abstraction and the induced intensification of karst processes, occurs if quarrying breaches artesian confinement. In the zone where artesian hydrogeological settings still predominate, sulphur ores (at the top of the gypsum bed) and overlying clays for cement industry are mined extensively by open pits. These operations are exemplified respectively by the Jazovsky sulphur quarry (Fig.4) and by the Nikolaevsky clay quarry; both breaching the thickness of the confining clay. Such quarrying schemes had been based on the widespread but misguided belief among local geologists that the gypsum is an aquiclude that would prevent hydraulic connection of the underlying regional aquifer with the quarried sequences above the gypsum. In reality, pre-existing artesian cave systems within the gypsum provide a highly efficient hydraulic connection through the bed (Klimchouk, 1997), and this has caused major problems for the mining operations.

Water withdrawal from both the Jazovsky and Nikolaevsky quarries has been increasing dramatically during the initial period of the operations, reaching respectively 100,000 and 280,000m^3/day. The following consequences have occurred in groundwater circulation (Andrajchouk & Klimchouk, 1993):

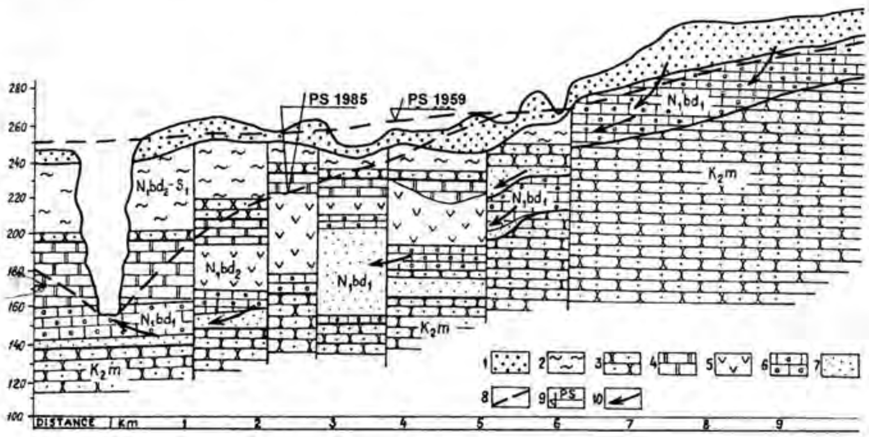

Fig.4. Geological-hydrogeological profile of the Jazovsky sulphur deposit area (After Andrajchouk & Klimchouk, 1993). 1 = Quaternary sediments (sands), 2 = clays, 3 = sandstones, 4 = epigenetic sulphur-bearing limestones, 5 = gypsum, 6 = bioherm limestones, 7 = sands, 8-9 = potentiometric surface for different years, 10 = directions of underground water flow.

1. Potentiometric surfaces have fallen dozens of meters (up to 90m at the Jazovsky site; see Fig.4) and hydraulic gradients have increased drastically.

2. Local areas of upward flow in pre-existing groundwater systems have been reversed into zones of downward recharge; piracy of surface runoff has occurred. Pirated surface stream water comprises up to 25% of the total withdrawal from the main open-cut mine in the Jazovsky deposit (Ivanov et al, 1985), and the Zubra river, the course of which lay a few kilometres from the Nikolaevsky quarry, has lost almost all of its flow.

3. Extensive drawdown cones have formed in the potentiometric surface, affecting an area of up to 100km^2 at the Jazovsky deposit.

4. Velocities of underground water flow have increased significantly, being up to 2.5km/day near the Jazovsky deposit and up to 10.2km/day near the Nikolaevsky deposit.

As a result of the sharply accelerated circulation involving both surface waters and waters from the underlying aquifer, rates of gypsum dissolution and of cavity enlargement have increased dramatically. Dissolution rates in the region, variously estimated by hydrological-hydrochemical and standard-tablet techniques, are normally about 0.2-0.4 mg day^{-1} cm^{-2} under the natural conditions of this zone. They have increased to 1.6 mg day^{-1} cm^{-2} in the Jazovsky deposit and are as high as 28.2 mg day^{-1} cm^{-2} in the Nikolaevsky deposit' due to the effects of the above factors (Klimchouk

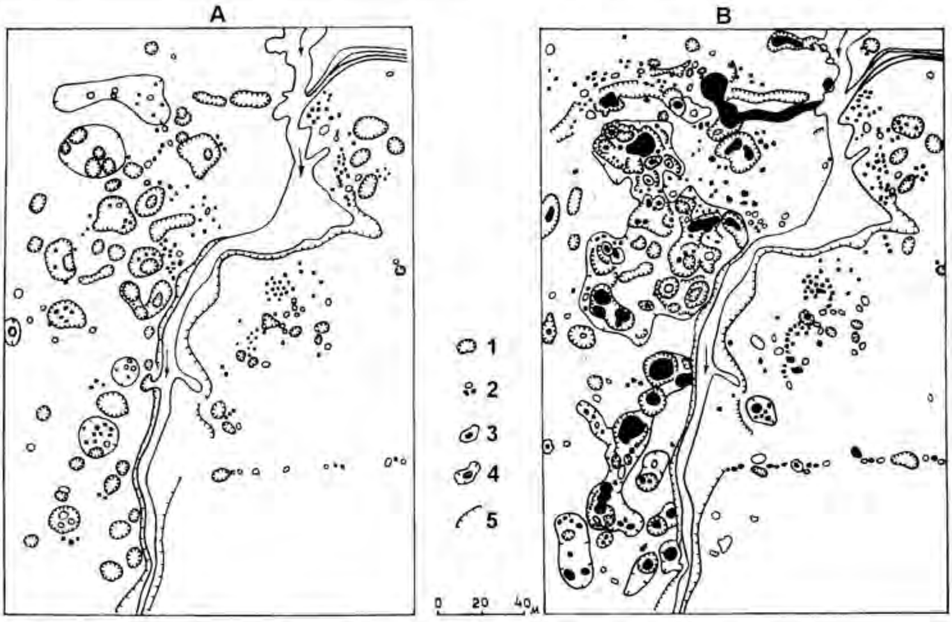

Fig. 5. Activation (A) and stabilization (B) of surface karst development induced by quarrying operations and abandonment at the quarry in the vicinity of the Nikolaevsky clay deposit. 1 = new collapses, 2 = small old and new (black) collapses, 3 = karst features with lakes, 4 = old but re-activated karst features, 5 = vertical and steep ledges.

et al, 1988; Ivanov et al, 1985). Also, washing out of unconsolidated fill has contributed to an overall increase in permeabilities.

The above processes have led to a sharp increase in collapses at the surface within extensive surrounding areas. In the vicinity of the Jazovsky deposit there were 943 collapse dolines recorded up until 1988, and of these, 260 (27.6%) had formed during the preceding decade. Catastrophic collapse development has affected the area of the Nikolaevsky quarry as well (Fig. 5), causing severe damage to surface constructions and communications. In the latter case huge water inflows and intense collapse development eventually caused flooding and abandonment of the quarry. The potentiometric surface was established above the bottom of the clay deposits due to artesian head, and many newly-formed collapse dolines became lakes (Fig. 5-B).

6. Construction of dams and reservoirs

The construction of dams and reservoirs in gypsum karst areas locally increases hydraulic gradients and raises a water table in previously unsaturated rocks. Both effects can lead to enhanced dissolution if gypsum rocks occur at the foundation of a dam construction or within the zone of influence of a reservoir. This can lead to leakage from a reservoir and cause collapses affecting dams and/or the areas surrounding reservoirs. The relevant practices and hazards, and the methods of their assessment, are reviewed in James & Lupton (1978), James (1992) and Pechorkin (1969). As dissolution of gypsum is much faster than that of limestones, these problems are potentially more severe in gypsum karst than in carbonate karst terrains.

There are numerous examples of dam failure and reservoir leakage due to accelerated development of gypsum karst in many countries. The most infamous failure associated with gypsum was in California, USA, where the St Francis Dam failed in 1928, at the cost of more than 400 lives and millions of dollars (Hill et al., 1929, cited by James, 1992). The problem was associated with dissolution of gypsum that was cementing and filling fissures in gypsiferous conglomerate in the dam foundations. Among other examples, the Hondo and Macmillan dams in New Mexico, USA, are of interest, as they are associated with gypsum and limestone in which very large dissolutional cavities had formed. The proposed reservoirs behind the Hondo and Macmillan dams were never impounded, as leakage was too rapid. In the latter case, huge underground dissolution channels with a capacity estimated at 50 million m^3 had been reported. Emplacement of a cement-grouted cut-off in the foundations of the Red Rock Dam in Iowa, USA, required the injection of about 2800 metric tons of cement into boreholes that intercepted underlying dissolution conduits (James, 1992). The Huoshiro reservoir in China, with a capacity of 4.7 million m^3, was built on a gypsum-limestone karst in Guizhou Province. After a period of water loss the reservoir eventually emptied through underground routes that connected a series of sinkholes in the reservoir floor to a resurgence point 400m downstream of the dam, where up to 237 L/s of water had been discharging (Yaoru & Cooper, 1997). Cases of emptying of smaller reservoirs impounded above gypsiferous formations are numerous in the USA, Western Ukraine, Russia, Siberia, Iraq, China and other countries.

The effect of direct river water action on gypsum outcrops and of a water table being raised

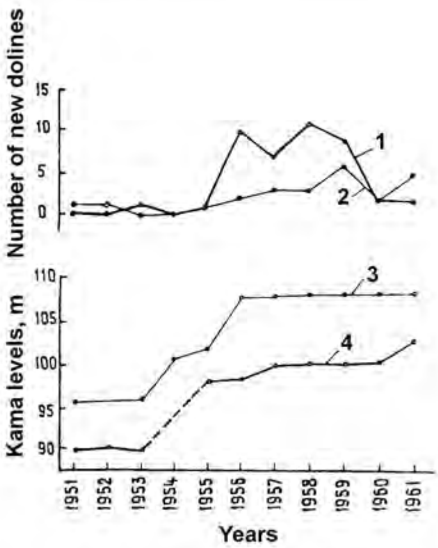

Fig.6. Dynamics of collapse processes in the coastal zone of the Kama reservoir (After Lukin et al., 1963).
1 = collapses on the lower and middle terraces,
2 = collapses on the high terraces,
3 = high flow levels of water in the Kama river near Khohlovka village,
4 = base flow levels at the same site.

within a gypsum sequence due to dam construction is exemplified by the Kama reservoir, created on the Kama river in the Pre-Urals, Russia, where the river flows entrenched into a gypsum sequence. A rise in water level of 10-15 m upstream of the dam, caused a related elevation of the water table within the gypsum of surrounding areas. Gypsum walls along the shorelines were directly exposed to the dissolving action of the reservoir water. The widening of open fissures in the gypsum outcrops during navigation season was measured, depending upon their orientation relative to flow, to vary from 0.2-0.4 to 2.5-3.0m. Five year long observations of particular gypsum boulders submerged in a small gulf, have shown dissolution rates varying from 0.5 to 1.2 kg day^{-1} m-2 (Pechorkin, 1986). Inside the gypsum massif, most active dissolution takes place within the fluctuation zone of the water table, which responds to a 5-7m seasonal change in the reservoir water level. Gypsum karst development has been greatly enhanced within 1 to 3km-wide zone along the reservoir coasts, resulting, particularly, in the formation of new collapses (Fig.6) and presenting severe land-use problems (Lukin et al, 1963; Gorbunova et al, 1992).

7. Collapse and subsidence hazards

Problems related to collapse and subsidence can be severe in intrastratal karst settings. They are recorded to cause widespread damage to various kinds of constructions, communication routes and other property, and even to cause loss of life. The extensive literature relating to subsidence includes hundreds of publications concerning gypsum karst. Mechanisms of breakdown propagation through an overburden, and the characteristics of collapse dolines in typical gypsum karst regions, are considered in Chapter I.10. Both the density and a rate of appearance of new collapses can be high in gypsum karsts. The problem is further complicated because collapse processes in gypsum karst can be greatly enhanced in response to human impacts, particularly in cases when such impacts modify a natural groundwater circulation pattern. This type of interaction is well illustrated in section 5 above.

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PART II

REGIONAL REVIEWS AND CASE STUDIES

Chapter II.1

Gypsum karst of the World: a brief overview

Alexander Klimchouk, Paolo Forti & Anthony Cooper

Introduction

On the global scale, surface outcrops of gypsiferous strata appear quite limited. This apparent scarcity can be explained by the relatively low resistance of gypsum to denudation effects rather then it reflecting an actual limited occurrence of sulphate rocks. The extent of territories where sulphate rocks are present at the surface or at depth is great: Ford & Williams (1979) estimated that gypsum/anhydrite and/or salt deposits underlie 25% of the continental surface (approx. 60 million km^2), while Maximovich (1962) calculated that the area of the continents underlain by gypsum/anhydrite alone is about 7 million km^2. As is demonstrated in Chapter I.4 and elsewhere in this volume, karst processes operate extensively in intrastratal settings, beneath various types of cover beds, where gypsum beds occur within at least the upper few hundred metres of the rock sequence. Taking this into account, gypsum karst appears to be a much more widely developed phenomenon than is commonly believed.

The largest areas of sulphate rocks are found in the Northern hemisphere, particularly in the United States, where they underlie 35 to 40% of the nation's land area (Chapter II.2), and in Russia and surrounding states, where Gorbunova (1977) estimated an extent of 5 million km^2 in the former USSR. However, many other countries within the American continents, Europe and Asia host important, and commonly quite extensive, gypsum karst. Detailed characteristics of many of these are provided within the national reviews comprising later chapters of this volume. The aim of this chapter is to present a brief overview of the geographical distribution of gypsum karst in the world, with particular reference to those areas that are not described separately, either due to a real scarcity of data or because editors were unable to involve local experts. The general order of the reviews begins in the Americas and proceeds towards the east.

The first brief global reviews specifically dealing with gypsum karst were provided by Maximovich (1955, 1962). Since then knowledge of gypsum karst, in terms of its morphological and hydrogeological peculiarities, development mechanisms and geographical distribution, has increased dramatically. Recently the global distribution of gypsum karst has been considered by Nicod (1992, 1993).

1. North America

1.1. Canada.

Sulphate rocks occur extensively throughout the Canada territories at a variety of depths below the surface, ranging from the subsoil level to deep-seated settings. The total extent of the sulphates is estimated at about 77,000km^2 (Quinlan & Ford, 1973, cited after Gvozdetsky, 1981), indicating that gypsum karst is well developed in the country. The most recent account is currently in press (Ford, 1997), and, regrettably, was not accessible as a source for this review.

In the Canadian Arctic Islands areas of gypsum outcrop with dolines are present on Elsmire Island, and on the islands lying to its south-west, where there are also many diapiric structures with gypsum caprocks. Doline fields are also known on Devon Island (Gvozdetsky, 1981).

North of the Franklin Mountains, on the eastern flank of the Rocky Mountains system (North-West Territories), dolines associated with of sulphate rock dissolution occur beneath thick calcareous shales. In particular, large collapse dolines are reported (reaching 100 to 180m in diameter and more than 40m deep to water level) in the Vermilion Creek area (Van Everingden, 1981; Ford & Williams, 1989). Their formation is related to vertical through structures (VTS) that propagated upwards from a buried gypsum horizon. Large gypsum domes also occur here. The belt of sulphate rocks continues from the Franklin Mountains to the western edge of the Canadian Shield. Various indications of gypsum karstification include dolines, karst trenches, breccias and springs (Gvozdetsky, 1981). Middle Devonian gypsum and anhydrite occur extensively in the area south of the Franklin Mountains, particularly at the base of the Presqu'ile Reef at Pine Point in the North West Territories. Sulphate dissolution at a depth of about 100m triggered VTS development in overlying, chiefly carbonate, sequences that are capped by glacial till (Ford & Williams, 1989).

Vertical through structures, active subsidence and sulphate-rich groundwater are associated with gypsum dissolution in the central part of Rocky Mountains of British Columbia (Wigley et al, 1973). The gypsum here is of Devonian age, up to 120m thick, and sandwiched within a mainly dolomitic sequence.

An extensive area containing immense interstratal deposits of Middle Devonian salts and gypsum (the Elk Point Formation) stretches across the Canadian part of the Great Plains, through Alberta and Saskatchewan to south-western Manitoba. West of Lake Athabaska, the Wood Buffalo area presents gypsum karst in the Chinchaga Formation, which is overlain by about 40m of dolostone. Numerous collapse dolines, including recent steep-walled examples, locally form 15% of the land surface (Leung, 1981, cited after Cruden et al, 1981; Tsui & Cruden, 1984) and indicate intense intrastratal karstification within the gypsum. In Saskatchewan there are many vertical through structures associated mainly with salt dissolution, as well as the huge Hummingbird Trough, which is believed to reflect intrastratal evaporite dissolution (Ford & Williams, 1989). An area, with a more varied set of karst forms, including caves, lies west of Lake Winnipeg, and karstified Silurian salt and gypsum deposits are known between lakes Huron and Erie (Gvozdetsky, 1981).

Gypsum karst dolines and karst breccias within an interbedded gypsum/carbonate sequence are known in the James Bay area, in the southern part of Hudson Bay (Gvozdetsky, 1981). Extensive areas of Mississippian gypsum either at subsoil level and/or beneath glacial till occur in the Canadian Maritimes (Nova Scotia, New Brunswick and Prince Edward Island provinces), displaying well-developed surface (dissolution, collapse and subsidence dolines, and trenches) and underground (vertical solution pipes and caves) karst features, studied systematically by Moseley (1996 and references therein). Locally dolines up to 20m deep are so closely spaced that they are separated only by narrow ridges or small residual hills. Some 30 caves have so far been explored in the region, the largest being about 400m long (Hayes Cave, Nova Scotia). Active dissolution and subsidence have also been reported from Newfoundland (Sweet, 1977).

1.2. United States.

Sulphate rocks of various ages, but predominantly of Palaeozoic origin, are distributed widely throughout the United States, where they underlie about 35 to 40% of the continental territory. Important summarizing works include those of Quinlan (1978), Quinlan et al (1986), Dean & Johnson (1989), Johnson (1997) and Chapter II.2 in the present volume. The huge Permian basin in the south-west of the United States is the largest and most conspicuous gypsum karst area, and includes Jester Cave, the longest gypsum cave known outside the Ukraine. Many other significant caves are known in the Gypsum Plain area of New Mexico. Other significant karst areas are found in the Illinois basin, the Michigan basin, the Forest City basin, the Black Hills area of South Dakota, and parts of Texas, Wyoming and other western states (see Chapter II.2).

1.3. Cuba.

Cuba is the only country in Central America where scientific investigation of gypsum karst has taken place. Gypsum outcrops are located close to Punta Alegre and Turignano, in Ciego de Avila province, some 600km east of Havana, but only the Punta Alegre area has been studied.

At Punta Alegre the gypsum outcrop is the caprock of a large diapiric structure that shows a classic concentric structure, with Miocene gypsum uplifted in its centre, and with an Oligocene colluvial border (Chiesi et al, 1992; Fagundo et al, 1993). The extent of the gypsum outcrop is about 20km^2, consisting mainly of detrital aggregates of different sized crystals, though the sequence commonly includes limestone, sandstone or marl clasts and gravels. Small outliers of the former limestone cover (5 to 10m thick) commonly overlie the gypsum, locally hindering its dissolution and giving rise to a peculiar "mushroom field" landscape that is typical of the sub-horizontal part of the diapir.

The whole area of gypsum outcrop is characterized by well-developed exokarst forms. Numerous dissolution dolines are present, and almost all of them have open sinkholes in their floors. The largest doline is over 200m in diameter and about 50m deep. Karren are developed over each exposed gypsum face and their development and shape are closely related to the gypsum crystal size and the presence and frequency of clasts encapsulated within the gypsum rock.

Deep karst is represented by several small caves, the longest being about 70m in length and the deepest about 27m deep. All the caves lead from sinkholes and their deepest points are normally at base level. No resurgences have been detected in the entire area. The main deep morphology is represented by pits and small canyons; no large chambers or horizontal passages have been observed.

Despite their limited development, the Cuban gypsum caves are very rich in secondary chemical deposits (large calcite flowstones, stalactites, blades and gypsum flowers). Most of the calcite deposits are the result of incongruent dissolution of gypsum by seepage water with a very high CO2 concentration caused by the presence of a tropical vegetation cover. The widespread gypsum flowers are related to the area's high temperature (25 to 35°C), which encourages rapid evaporation of seepage water.

2. South America.

Small gypsum outcrops exist along the Andean chain between Venezuela (Forti, 1993b) and the far southern part of the South American continent, but very little is known about their geological settings and karst. Nevertheless, in most South American countries gypsum deposits represent an important economic resource and, as in the case of Venezuela, they have been severely ravaged by quarrying.

2.1. Argentina.

Argentina hosts extensive and thick gypsum deposits, the main outcrop areas being in the Neuquen and Mendoza provinces, where the gypsum sequences belong to the late Jurassic Aquilco Formation. These beds normally consist of several hundred metres of microcrystalline gypsum and anhydrite, strongly deformed by the tectonic stresses that have affected the Andes and which have locally imposed a vertical dip upon the Aquilco Formation (Forti 1993a, Forti et al, 1993). In some cases, such as in the area of Las Legnas, about 200km from Mendoza in the central part of the Andes, gypsum outcrops extend vertically for more than 2,500m, reaching altitudes greater than 4,500m.

Local climate, which is cold and dry at the foot of the Andes and is characterized by heavy snow falls, has a strong influence on the external karst morphology. The high mountain karst morphology is characterized by a high density of small dolines, commonly covered by thick deposits of gypsum sand, derived by aeolian erosion, which prevent the development of karst microforms such as karren. Inside the gypsum sand some sub-vertical condensation-dissolution tubes ("Gypsum chimneys") have developed due to the peculiar climate of the area (Forti et al, 1993). Such forms are restricted to the gypsum karst of Argentina. The highest areas, and some of the sub-vertical slopes of the higher gypsum outcrops, are characterized by the presence of high (some tens of metres) gypsum pinnacles, while on those slopes over which snowmelt causes a water flow, peculiar "megakarren" develop, with lengths of 100 to 200m and from 2 to 10m wide. These forms have been described, but not studied in detail (Salomon & Bustos, 1992).

Gypsum outcrops at lower altitudes are characterized by large dolines and blind valleys. Some karren and other microforms have been observed where the gypsum rock is not highly tectonized. Suffosion dolines in thick alluvial deposits that overlie the gypsum are the most common forms associated with gypsum outcrops in these areas. Some of them are 100m in diameter and 80 to 100m deep, and occasionally they contain lakes.

The largest gypsum cave known in Argentina and in the whole of South America is the Cueva del Leon (Zapala area, Neuquen Province) comprising over 700m of sub-horizontal passage and containing a river (Lipps, 1986). It represents the middle part of a hydrogeological system that feed a perennial spring several hundreds metres beyond, and some tens of metres below, the bottom of the cave. It has been proved that over 70% of the water flowing inside the cave derives from condensation. Condensation corrosion domes in passage ceilings are the cave's most common morphological feature. No secondary deposits are found in the cave, except for large and widespread deposits of gypsum powder, the genesis of which is closely related to the unusual "dry continental cold desert" climate of the area. Recently some tens of smaller gypsum caves have been explored, and large karst springs have been found at the foot of the main gypsum outcrops. This suggests that the exploration potential of the gypsum of Argentina is far greater than has previously been appreciated.

3. Europe

3.1. Norway.

Gypsum karst associated with the (Middle and Upper Carboniferous) Gipsdalen Group is described in the north-western part of Nordenskiold Land in West Spitsbergen (Pulina & Postnov, 1989). Despite the occurrence of permafrost and long winters with a polar night, underground water circulation is well developed and it causes intense karstification. There are some large dolines and karst springs showing underground channels.

3.2. Great Britain.

In Great Britain the most spectacular gypsum karst development is in the Zechstein (Upper Permian) gypsum, mainly in north-eastern England (Smith, 1972; Cooper, 1986, 1989, 1995). In the Midlands less well developed gypsum karst is found in Triassic gypsum in the vicinity of Nottingham (Cooper, 1995). Along the coast of north-east England, south of Sunderland, well-developed palaeokarst, with magnificent breccia pipes, was produced by dissolution of Permian gypsum (Smith, 1972, 1995). In England, only one small gypsum cave has been surveyed and recorded (Ryder and Cooper, 1993). From studies of subsidence and boreholes, a large actively evolving phreatic gypsum cave system has been postulated beneath the Ripon area. The rate of gypsum dissolution here, and the effects of associated collapse, lead to difficult civil engineering and construction conditions, which can also be aggravated by the effects of water abstraction (Cooper, 1988, 1995). Details of gypsum karst in Great Britain are provided in Chapter II.3.

3.3. France.

The main karstified gypsum sequences in France include gypsiferous Triassic strata in Provence and those in the Alps near Beaufortin and Mont Cenis, and Palaeogene (Lutetian and Ludien) gypsum in the Paris Basin (Nicod, 1976, 1992, 1993). Gypsum has long been exploited in mines (the Catacombs) and pits beneath Paris, giving rise to the English term "Plaster of Paris". Natural gypsum caves have also been found hereabouts (Soyer, 1961). Recently, important explorations took place in a cave named REseau Denis Parisis, accessible via an underground gypsum mine in Bethemont-la-Foret in the Val-d'Oise, which undercut the cave passages (Beluche, Le Kens & Teyssier, 1996). The natural passages form a rectilinear network over 1km in length and display morphology that appears typical of artesian caves formed by upward recharge [the impression of A. Klimchouk from the map and photos published in the above cited work]. The cave is now the longest gypsum cave in France. The estimated length of passages undercut by the entire mine workings is about 7km. They have no relation to the modern surface and provide an outstanding example of an intrastratal karst.

The second longest gypsum cave in France is the 525m-long Grotte de Champ-Bernard, developed in the Triassic gypsum of the Tarentaise valley in the Alps (Nicod, 1992). Much of the Alpine gypsum karst is actively evolving and related collapse is common (Julian and Nicod, 1990; Nicod, 1992, 1993). Construction of the Mont Cenis Reservoir on gypsiferous strata in the Alps was made difficult by the effects of ongoing gypsum dissolution (Deletie et al, 1990). Other geological hazards associated with gypsum karst include unfavourable construction conditions and subsidence around Paris (Arnould, 1970; Toulemont, 1984), at Draguignan and near Trans-en-Provence (Nicod, 1991). A more extensive review of gypsum karst in France is provided in Chapter II.4.

3.4. Switzerland.

Some gypsum karst in Triassic rocks is known in the Swiss Alps, in the western part of the Bernese Oberland, where an intensely karstified locality is marked by closely-spaced dolines and gypsum hills. The St. Leonard Cave is 300m long and contains a lake (Bernasconi, 1976).

3.5. Germany.

Germany has extensive gypsum karst developed in and upon Upper Permian (Zechstein) and Triassic gypsum sequences, with minor amounts in Jurassic rocks. The Permian succession, containing thick gypsum interbedded with well-developed carbonate aquifers, has produced some of the world's most spectacular gypsum karst, which is continuing to develop in many places, leading to subsidence. The most significant gypsum karst belt borders the Thuringian Basin on the southern flank of the Hartz Mountains, a region that has long been known for its gypsum caves (Pfeiffer and Hahn, 1972). The caves have a history of exploration and scientific examination dating from the time of Gripp (1912). It is thus natural that many gypsum cave features were originally named in Germany. The work of Biese (1931) was influential in classifying gypsum cave features, dividing them into Lufthöhlen (cleft caves), Laughöhlen (solution caves) and Quellungshöhlen (bulge caves); features that were further classified and studied by Reinboth (1971) and Kempe (1972). Other features first described in German gypsum caves include the Laugdecke (flat solution roof) and Facette (sloping facet wall). The German names take precedence over their English translations and should always be used when describing these features (Moseley, 1996). The gypsum karst gives rise to subsidence problems, extensively described by Hundt (1950) and Reuter (1963, 1973), and has engineering implications for construction in the affected regions, including cities such as Stuttgart (Ströbel, 1973). A detailed account of German gypsum karst is presented in Chapter II.5.

3.6. Spain.

Spain hosts some of the most significant gypsum deposits in Western Europe, with some 30,000km^2 of gypsum outcrops (Ayala et al, 1986), composed of rocks ranging from Triassic to Quaternary in age. A general review of gypsum karst in the country, and more detailed descriptions of particular areas, are provided in Chapter II.6.

Triassic gypsum (of Keuper facies) crops out mainly within the Betic mountain range, though there are also significant outcrops in the Pyrenees and Iberian ranges. Significant karsts are reported in the Baena (Cordoba) Fuente Camacho (Granada), Estella-Allo (Navarra), Gobantes-Meliones (Malaga), Archidona and Antequera (Malaga), Caravaca (Murcia), Vallada (Valencia) and Villena (Alicante) areas. The Vallada area contains the deepest gypsum cave in the world (Tunel dels Sumidors, -210m). Gypsum karst in Palaeogene gypsum is developed in the area north of the Ebro basin, close to the edge of the Pyrenees, where collapse and subsidence induce considerable environmental problems (Gutiérrez et al, 1985). Neogene gypsum successions are more widespread. The most noteworthy outcrops, displaying evidence of karstification, are those of Estremera (Madrid; Eraso & Lario, 1988) and Jadraque (Guadalajara) in the Tajo, Zaragoza and its surroundings in the Ebro basin (Gutiérrez & Gutiérrez, 1995), Calatayud in the Iberian range (Gutiérrez, 1996), and the Sorbas basin in the Betic range (Pulido-Bosch & Calaforra, 1993; Calaforra, 1996). The latter area presents a remarkable variety of both surface and sub-surface karst forms, including the longest gypsum cave in the country (Cueva de Aqua, 8,350m) and many other significant caves (see Chapter II.6).

3.7. Italy.

Early publications about gypsum karst in Italy date back to the end of the last century, and the first fundamental review was that of Marinelli (1917). Many small and some larger gypsum outcrops are scattered throughout the country, from the Alps in the north to Sicily in the south. In the Southern Alps gypsum karst is associated with small areas where highly tectonized Permian and Triassic gypsum units crop out, or lie beneath unconsolidated cover. In the Northern Apennines the gypsum of the Triassic Burano Formation crops out locally (as in the Upper Secchia Valley) giving rise to the Poiano spring, which discharges part of the flow from a deep-circulation system. The same formation occurs at depths of several hundreds metres in the Central Apennines, but almost nothing is known about deep-seated karst here. The most significant and well-studied gypsum areas are composed of Messinian gypsum in Emilia-Romagna (over 100km^2) and Sicily (over 1,000km^2). The former area contains the longest gypsum cave in the country (the second longest gypsum cave in the world outside of the former USSR), the Spipola-Aquafredda system, which is 10,500m long. Much exploration and many detailed studies have taken place in the gypsum karst of Italy, as reviewed in Chapter II.7, where the more important of the hundreds of existing publications are referred to.

3.8. Albania.

Some Miocene and Triassic gypsum deposits are known in Albania. The Miocene gypsum normally gives rise to intrastratal karsts, characterized by suffosion dolines and some karst lakes. No other macro- or micro-forms have been described associated with these rocks, and no research has been undertaken to detect caves.

Triassic gypsum is known in diapirs that form the wide mountain chain Mai i Bardhe (the

White Mountains), which reach a height of 1,965m in the eastern part of the country, close to the border with Macedonia. The gypsum here is highly tectonized and fractured, and is commonly covered by a thick deposit of gypsum powder, produced by meteoric degradation of the gypsum rock. The landscape of the area is typified by the presence of thousands of small dolines, the floors of which are filled by deep gypsum powder deposits. Small karren and other micro-forms are visible on the less tectonized gypsum blocks. No large caves are known in the Triassic gypsum of Albania. Only a few sub-horizontal tectonic caves, not exceeding 20m in length, or small, rounded, vertical sinkholes, have been observed (Bassi & Fabbri, 1996).

3.9. Poland.

Deep-seated karst phenomena are known in the Upper Permian (Zechstein) gypsum of the Sudet area. However, gypsum karst is better developed in the Neogene (Badenian) gypsum unit that occurs widely in the south of the country, in the transition zone between the Western European platform and the Carpathian foredeep. Gypsum karst is described by Flis (1954), Bobrowski (1963), Osmolski (1976), Pulina & Liskowski (1986), Woloszyn et al (1986) and others. In the Nida Basin the gypsum unit is exposed locally due to denudation of the original cover-beds, or is covered by glacio-fluvial sands. Dolines are common, most of them being due to collapse and subsidence rather than dissolution (Flis, 1954). Locally areas with a very high density of dolines turn into karst troughs. Some of these forms, with emerging and disappearing streams running through them, are considered to be analogous to poljes. Small caves are numerous, and most of them are simple passages related to contemporary streams (Woloszyn et al, 1986). The largest so far discovered is the 280m-long Scorocicka Cave; other caves have lengths of a few tens of metres.

Practical difficulties associated with gypsum karst include the effects of collapses, which cause damage to constructions, and water supply problems. Gypsum karst is also believed to be involved in the origin of native sulphur deposits that are associated with the Badenian gypsum (Osmolsky, 1976; Pulina & Liskowski, 1986).

The same gypsum bed found in southern Poland extends into the Western Ukraine where it hosts well-developed intrastratal karst with extensive maze caves, but the karst style in Poland differs substantially from that in the Ukraine. The reasons for this are not yet fully understood, but they are presumably related to the different neotectonic, and hence palaeo-hydrogeological, histories of these regions.

3.10. Ukraine.

There are two major regions of gypsum karst in the Ukraine: the Podol'sko-Bukovinsky region in the Western Ukraine and the Donetzk region in the east of the country. Both regions lie within the large Eastern European Plain, which has formed upon the structural platform of the same name (see Chapter II.8).

The great gypsum karst of the Western Ukraine is associated with the Miocene (Badenian) gypsum and provides the world's most outstanding example of intrastratal gypsum karst and speleogenesis under artesian conditions. Differential neotectonic uplift has resulted in part of the territory being deeply entrenched by river valleys, such that the gypsum strata have been wholly drained and vast maze caves have became accessible. Five of these are the world's longest gypsum caves. Major deposits of native sulphur known in the region are related genetically to gypsum karstification under artesian conditions (Klimchouk, 1997b). Detailed descriptions of the region's gypsum karst, which are presented in many works, including those of Dubljansky & Smol'nikov (1969), Andrejchuk (1984, 1988), Klimchouk & Andrejchuk (1986, 1988) and Klimchouk (1986, 1990, 1992, 1997a), are summarized in Chapter II.9.

The karst in the Donetzk region is developed in gypsum beds that form part of a Lower Permian evaporate formation. Its features include dolines, larger depressions and caves; the longest known cave is 150m.

3.11. Romania.

The same Badenian sequence that extends through the Western Ukraine, continues into Romania, where it links the Eastern and Southern Carpathians sectors. The gypsum bed is discontinuous here, and karst, which is reported only locally, is represented by dolines and small caves (Ponta, 1986).

3.12. Baltic states (Lithuania and Latvia).

In the western part of the Eastern European Plain, gypsum karst in Devonian sequences occurs in Lithuania and, locally, in Latvia. Details of these areas are given in Chapter II.10.

3.13. European Russia.

The Russian part of the Eastern European Plain contains some of the world's most extensive gypsum karst regions, all representing different stages of intrastratal karst development. The most important of these regions are Pinego-Severodvinsky in the north (Caves..., 1974), Volgo-Kamsky in the centre (Karst phenomena..., 1969) and the pre-Urals in the west. They are reviewed collectively by Gorbunova (1977) and, briefly, in Chapter II.8 of this volume, but the pre-Ural region is considered separately in Chapter II.11.

At this point it is worth recording the most extreme northerly example of gypsum karst in European Russia, which is not reviewed in the chapters mentioned. Lower Carboniferous gypsum is exposed locally on the islands of the Novaja Zemlja archipelago. Karst forms are represented by large closed depressions and small dolines (Jushkin, 1975). Inclusions of relatively poorly soluble carbonate cause the formation of mushroom-like features with thin gypsum pedestals and carbonate caps. Tumuli (gypsum mega-bubbles) are also common.

4. Asia

4.1. Asiatic Russia.

The boundary between European and Asiatic Russia runs through the Kerch Channel between the Black Sea and Asov Sea, then follows the Kuma-Manych depression to the Caspian Sea, and thence along the Ural river and the axis of the Ural Mountains to the Arctic Ocean.

4.2. Siberia.

The huge terrain of Western Siberia, which extends behind the Urals, is composed mainly of sedimentary rock units with no significant karst. Eastern Siberia, to the east of the Enisej river, encloses many gypsum karst areas within the Siberian Platform. Gypsum karst develops more intensely than carbonate karst in the permafrost zone, which covers most of the region (Korzhuev, 1973, 1977; Gvozdetsky, 1981). Karst phenomena are recorded (though poorly studied) associated with the gypsum beds in various Lower Palaeozoic sequences, in high parts of the western Enisej Basin (Norilsk Plateau, Putorana Plateau) and in many areas within the vast basins of the Anabar, Hatanga, Olenek, Viljuj and lower Lena rivers. Gypsum karst is commonly associated with salt karst in extensive intrastratal deposits, as well as in the caprocks of the salt diapirs. Surface forms are represented by dolines and larger depressions, many of which are occupied by lakes. In the Tajmyr peninsula there are dolines up to 200m in diameter and 60m deep. Filippov & Shkol'nik (1988) have studied some 12 caves in a 2m-thick Upper Ordovician gypsum bed cropping out in the Viljuj valley. The largest cave is 95m long; all of them display well-marked polygonal cross-sections, with flat ceilings and inclined facets. Cave development is believed to have occurred under confined conditions with later modification by back-flood waters from the Viljuj. Ice formations in the form of stalactites, stalagmites and crystals are abundant in the caves.

The most extensive gypsum karst is in the south of the Siberian Platform, in the Angara and Upper Lena basins, where it is associated with Lower Cambrian (Angara Formation) and Upper Cambrian (Verkholensky Formation) gypsiferous rocks. Several prolonged episodes of karstification caused a 50 to 500m reduction in the thicknesses of some gypsiferous horizons, resulting in the formation of laterally extensive breccia horizons, vertical through structures, and large dissolutional depressions on the surface (Vologodsky, 1975). Modern karstification is also in progress, represented by numerous collapse dolines (see Chapter II.12). There are many caves in gypsum/anhydrite/dolomite sequences, the largest of which are Balaganskaja (1,200m) and Khudugunskaja (650m). Both of these are fine examples of rectilinear multi-storey maze caves, which probably developed under confined conditions. Creation of the Bratsky reservoir on the Angara river led to greatly intensified gypsum karstification, causing severe practical problems (Vologodsky, 1975). Gypsum karst in the south of the Siberian Platform is reviewed in Chapter II.12.

4.3. North Caucasus.

Many gypsum karst areas are scattered between the Asov and Caspian seas along the northern part of the Caucasus Mountains, forming a discontinuous belt about 600km long. The Upper Jurassic gypsum ranges in thickness from few metres to 100m or more. Due to the heavily folded tectonic structure and geomorphological settings that vary from high mountains to plains, a variety of modes of gypsum occurrence exists. Gypsum karst and caves are described in many publications, including those by Zubashchenko, (1938), Gvozdetsky (1965), Musin & Magomedov

(1971), Kazanbiev (1975), Gorbunova (1977), Makukhin & Molodkin (1988), Sukhovej (1992) and Ostapenko (1993, 1994).

Exposed gypsum karst settings are displayed in gypsum massifs within the main plateau of the Skalisty Range and its northern slopes, though cover beds of sandstone, siltstone or clay are more commonly present. In the eastern (Dagestan) part of the region, gypsum/dolomite beds underlie limestones. Some areas are characterized by well-developed karst landscapes, with numerous dolines, blind valleys and intermittent streams. Many caves are known in the region, with lengths ranging from a few hundred to 1,000m. The longest caves are Popova (1,670m), Ammonal'naja (1,460m/-110m) and Setenej (980m). All appear to be linear caves with active streams and multiple entrances. Some caves are nearly horizontal, with two or more storeys; others are inclined with some vertical drops. Large collapse dolines and depressions are also present. A distinctive feature is the widespread presence of carbonate breccias, which wholly or partially replace the dissolved gypsum beds in many parts of Dagestan (Musin & Magomedov, 1971). These breccias range in thicknesses between 20 and 130m, the residual thickness normally being about half that of the undissolved gypsum/dolomite units preserved within adjacent structures. Active karst development in deep-seated settings is indicated by springs and boreholes that yield sulphate waters enriched with H2S.

4.4. Turkey.

In the Sivas Basin of central eastern Turkey, gypsum karst has developed in the late Miocene Ekincioglu and Hafik formations, which are covered by Pliocene and Pleistocene clastic rocks. Occurrences of the gypsum beds are highly irregular, due to the effects of tectonic and karstic deformation. In the Ekincioglu Formation the gypsum occurs as massive lenses of coarsely crystalline or layered rock up to 100m thick, locally intercalated with siltstone and sandstone beds. In the Hafik Formation up to 750m of gypsum and rock salt are present. Karst features are represented by dolines, swallow holes, dry valleys, intermittent streams and springs. The presence of caves has also been described, but their character and dimensions are not specified (Ifran & Ozkaya, 1981; KaHaroólu et al, 1997). Deep-seated gypsum and anhydrite sequences are also reported in the area of the Dicle Dam reservoir in south-eastern Turkey.

4.5. Israel.

Gypsum and anhydrite are present within the caprock of the Mount Sedom diapir, close to the Dead Sea. Although the most prominent karst features in this area are associated with salt dissolution, the sulphate rocks are also karstified locally.

4.6. Syria.

Gypsum formations, commonly intercalated with halites, are widespread in the central eastern part of Syria, where their maximum thickness reaches 300 to 400m. Most of the outcrops are along the right bank of the Euphrates valley. The gypsum is mainly of Mid Miocene age, although Jurassic anhydrite formations occur locally in the same area.

From the karstological viewpoint the gypsum of Syria is poorly studied. However, the area of Ratla, near the city of Raqqa, has attracted recent speleological attention (Calandri & Grippa, 1991;Voigt & Schadwinkel, 1995). The gypsum outcrop at Ratla is constrained between a gypsum cliff up to 50m high (that drops to the Euphrates valley) and the arid Syrian desert, and the Miocene gypsum is intercalated with minor marl and limestone beds. Extensive development of karst features, including dolines and caves, is reported in the area (Voigt & Schadwinkel, 1995). The arid climate, together with the effects of thermoclastic and aeolian weathering, prevent the evolution of well-developed microforms.

All the known caves are located in the gypsum cliff. The largest (also the largest gypsum cave in Asia) is Cater Magara, where 7,300m of passages have been surveyed by German cavers. The cave morphology is dominated a large passage with a stream and lakes, which generally trends sub-parallel to the cliff. This trunk passage commonly reaches 20 to 40m in width and has many sections of flat ceiling. The cave's structure is complicated by the presence of many labyrinth areas and boulder chokes, mainly lying along the left side of the main gallery. Vertical pits connect the cave with the floors of surface wadis (dry valleys), which provide additional water inflows during rainy periods. Abundant gypsum stalagmites and flowers occur in parts of the cave. Other significant caves include Taubenbrunnen (860m) near Cater Magara, and Rattla cave (about 100m).

4.7. Iraq.

Gypsum and anhydrite rocks within a Miocene evaporite sequence occur in the Kurd Mountains (the continuation of the Zagros system) in the north of Iraq, but almost nothing is known about any karst phenomena associated with these rocks.

4.8. Iran.

In south-west Iran, close to the border with Iraq, gypsum crops out in the Zagros mountain chain, where very thick Triassic and Miocene marine sequences occur. The upper beds include a 200 to 300m-thick marly/evaporitic unit (the Middle Miocene Gaghsaran Formation), comprising medium-bedded marls, siltstones and gypsum. The gypsum beds are 5 to 30m thick, and are normally represented by pure and compact microcrystalline gypsum with a centimetric to millimetric lamination.

Where it is thick and occurring in the shallow sub-surface, the massive gypsum is highly karstified, displaying surface landforms and complex cavities (Cucchi, personal communication). Dissolution dolines are widespread at the surface, commonly being shallow and symmetrical. Other common karst forms include blind valleys, collapse and suffosion dolines, and springs. Micro-rills and dissolution flutes or grooves (Rillenkarren and Wandkarren) are typically found on exposed gypsum faces. The morphology and extent of these forms are influenced by the presence of calcite veins, or marl and silt gravel inclusions. Tumuli are also widespread. Caves are developed within interbedded layers and/or along sub-vertical tectonic joints. The few explored caves show phreatic passage morphologies that are commonly 5 to 6m high and 8 to 10m wide, though locally modified by breakdown. Many of these cavities have been intersected by modern valleys.

Gypsum karst is known also in many areas east of the Persian Gulf and in the central parts of

Iran, where it is developed mainly in the Miocene gypsum caprocks of the many salt domes. Collapse dolines are the most common karst features.

4.9. Central Asiatic countries of the former USSR

(Kazakstan, Turkmenistan, Uzbekistan, Tadzhikistan, Kirgizstan).

This region can be divided broadly into two distinct parts, comprising plains to the north (the Caspian Lowland and Turan Plain) and mountains in the south and south-east. The gypsum karst of Central Asia is described in more than 100 publications, the more important of which are those of Gvozdetsky (1978, 1980), Gvozdetsky & Abduzhabarov (1977) and Mamatkulov (1988).

The north-west part of Kazakhstan and the adjoining part of Russia (north of the Caspian Sea) is occupied by the Caspian Lowland, where many salt diapirs arch the beds at different depths or crop out at the surface. They are commonly overlain by Lower Permian gypsum units that are intensely karstified, exhibiting dolines, dry valleys and small caves.

The Turan Plain extends to the west of the Caspian Sea, and encloses several gypsum karst areas. In the Ustjurt/Mangyshlak area karst is developed in nearly horizontal Miocene gypsum that is overlain by limestones. There are large dissolutional depressions, dolines, swallets and small caves in this area. Another intensely karstified gypsum area is known in the eastern part of the Betpak-Dala desert.

In the north-eastern part of the Chujsky depression there are many dolines related to Carboniferous gypsum. Some small (to 40m) caves are known in a Palaeogene gypsiferous sequence in the Badhyz area.

Many areas of gypsum outcrop are known in the mountainous region of Central Asia. Gypsum karst is known locally in the Neogene sequence of the Ilijsky and Karkarinsky depression of the Northern Tjan-Shan, but it is more common in the Pamir-Alay and northern Pamirs, where it develops in marine carbonate/gypsum and lagoonal gypsiferous sequences of Mesozoic and Cenozoic age.

In the south-east of Turkmenistan and the south-west of Uzbekistan, in the low altitude Gaurdak Mountains and in the Kugitang and Bajsuntau mountains, gypsum karst occurs widely in the Upper Jurassic Gaurdak Formation (over 100m thick, locally reaching 350 to 400m) and in the basal gypsiferous sediments of the Lower Cretaceous redbed sequence. In the Gaurdak area there are rare collapse dolines and caves revealed by sulphur quarries. Extremely intense karstification is characteristic for areas on the western slope of the Kugitang Range, where exposed gypsum surfaces display numerous dolines, funnels, small caves and shafts up to 50 or 60m deep. Large karst springs are connected to a circulation system that is fed from high altitude limestone areas. The adjacent plain holds large collapses with vertical walls, 25 to 40m deep to water level. Large inclined underwater galleries have been explored by diving to depths below 40m, and the water, which has a high sulphate content enriched in H2S, is inhabited by blind fish.

In the Bajsuntau Range the same formation is exposed at many localities at medium and high altitudes between sub-parallel limestone ridges. Extremely densely-packed dolines form a honeycomb pattern. For instance, in a typical gypsum karst area of $5km^2$ that is locally named "Mingchukur" (The Thousand Holes), there are about 2,000 dolines, which yields an average doline density of 400 per km^2 (Gvozdetsky & Abduzhabarov, 1977). There are also some relatively small caves, the largest of which, Kjaptarkhona, is more than 1km long with linear passages arranged on two levels; the lower level contains an active stream.

In the Tadjik depression karst develops in salt domes and in gypsum caprocks of Upper Jurassic and Palaeogene ages. Karst forms in gypsum include dolines, karren, swallets and caves (in the Babatag Range). A chain of gypsum karst areas (37 discrete areas are known) continues along the Vakhsh river, through the Northern Pamir, where Upper Jurassic and Lower Cretaceous gypsum occur on the northern slopes of the Zaalajsky Range and the Peter the First Range (at altitudes of 2,200 to 2,300 and 2,900m). The gypsum is either exposed or covered by morainic sediments. Collapse dolines up to 100m in diameter are common, and there are smaller closely-spaced dolines locally, with swallow holes in their floors. A 120m-deep gypsum cave has been explored in the Peter the First Range.

Gypsum karst in Palaeogene and Neogene rocks is known in the north-west and southern parts of the Fergana depression. Karst forms here include numerous dolines along dry valleys, karren, various positive residual forms, pits and caves. In the southern area the Akturpak cave has a length of 137m.

4.10. Afghanistan.

Collapse sinkholes associated with dissolution of a Neogene gypsum sequence are known in the Gilmend basin (Gvozdetsky, 1981).

4.11. Mongolia.

The presence of caves is reported in gypsum within an Upper Cretaceous sequence in the south-eastern part of the country (Klejner, 1976).

4.12. China.

Gypsum karst is developed extensively throughout China. It is associated with sediments of a variety of origins and ages, ranging from Precambrian to Quaternary. The most important gypsum karst areas lie within the Hebei and Shanxi provinces and along the Chang Jiang (Yangtze River) in the Sichuan and Hubei provinces. Some outstanding examples of gypsum karst in deep-seated settings have been recognised in China, and a more detailed review is presented in Chapter II.12.

5. Africa

The northern part of Africa is characterized by several gypsum outcrops of Triassic and Miocene age, scattered through Morocco, Algeria, Tunisia, Libya and Egypt.

5.1. Morocco.

In the Middle Atlas Mountains gypsum rocks are exposed in the Ain-Nokrah syncline, with some dolines and positive residual forms developed upon them (Nicod, 1993). In the High Atlas

Mountains, at Ammougguez, gypsum with some dissolutional features presented difficult tunnelling conditions for a hydro-electric scheme (El Ghorfi & Giafferi, 1991).

5.2. Algeria.

Algeria hosts several wide areas in which gypsum forms the major outcrops or occurs close to the surface. The karst features of two of these have been investigated. An area of Triassic gypsum at Djebel Nador in the eastern part of the country, about 60km from the Tunisian border, is the biggest diapiric structure in Africa. In this area several blind valleys, large dolines (up to 100m or more in diameter), and uvalas are developed. Most of the dolines are dissolutional, though there are also collapse dolines related to the evolution of deep karst phenomena. The area hosts one of the largest, and probably the deepest, gypsum cave system in Africa, the Dahredj Ghar Kef system (Calandri & Ramella, 1987). The Dahredj Ghar Kef system is a single hydrogeological tunnel, now cut into three different caves, separated by one erosional valley and a large collapse doline. The total length of the underground systems is over 2,400m, and the height difference from the highest water inlet to the spring is of 220m. The main cave morphologies comprise paragenetic galleries, over the ceiling of the main tunnel, and large breakdown chambers. In some parts of the caves gypsum stalactites and large secondary gypsum crystals are present.

In the western part of the country karst features are described in the Miocene gypsum of the Oranais area, close to Oran town, in Triassic and Miocene gypsum in areas further inland, such as El Abiod and Djelfa (Choppy & Callot, 1987), and in Miocene gypsum in the Ouled Fares area of the southern Dahra Mountains (Motyka & Witczak, 1992). The gypsum area near Oran is characterized by the presence of several small dolines and dry valleys, and by some caves, the structure of which is completely guided by tectonic factors. Most of these caves, which rarely exceed a depth of 20m and a length of 30m, have a very high CO2 content caused by biological decomposition of large deposits of organic matter in their lower parts. Triassic gypsum crops out in several large diapiric structures between El Abiod and Djelfa, and these present densely pitted landscapes with some larger dissolution and collapse dolines, swallets and small caves (Choppy & Callot, 1987).

Motyka & Witczak (1992) describe the karst features and hydrogeological settings of the Ouled Fares area, north of the Cheliff valley. Here Sarmatian (Sahelian) gypsum and sandstones rest uncomformably upon highly folded plastic clays of late Tortonian age. Gypsum is exposed widely due to the denudational removal of the overlying early Pliocene marine and continental deposits. Typically the gypsum beds contain small inclusions of sodium and magnesium chlorides and sulphates, which are more soluble than $CaSO_4$. Study of the chemistry of spring waters has allowed three groundwater circulation systems to be distinguished. Rapid sub-surficial circulation proceeds through large karst caves in gypsum beds, and the length of some underground streams can be several km, traced via separate caves of up to 500 to 600m. Shallow circulation systems include pore spaces within underlying sandstones and fissures or karst cavities at greater depths, and they are commonly connected to the sub-surficial systems. A deep circulation system is related to unexposed Miocene/Pliocene basal sediments and feeds distant recharge areas. All the systems are dominated by saline (2 - 14g L^{-1}) waters. Increasing TDS contents are accompanied by transition of water type from SO_4-Ca, through multi-ionic, to Cl-Na.

5.3. Libya.

A remarkable gypsum karst is associated with the Upper Jurassic Bir al Ghanam Format which extends from the Ar Rabitat/Bir area some 100km south-east of Tripoli, to and beyond border with Tunisia. Detailed speleological studies have been carried out by Hungarian spele gists (Kosa, 1980, 1981a, 1981b) on the largest continuous outcrop, which is known as the B Gharam Gypsum. The formation, which is about 400m thick and lies almost horizontally, con of two gypsum members separated by a largely dolomitic member. Both the upper and lo gypsum members are karstified and they host numerous caves. Some 7km of passage has b surveyed, including the longest, Umm al Masabih Cave, with a length of 3,593m. The caves mainly of linear type, carrying ephemeral streams (active during rain generated floods for sev hours a year), and they display vadose morphology. Bedding planes and joints have both h role in passage development. Gypsum layers of various quality, as well as minor intercalation dolomite, clay and marl, influence the shape of passage cross-sections.

Locally, the upper gypsum member is removed by erosion, and the plateau surface comp rock of the more resistant dolomitic member. Underlying caves cause collapse features to d lop, and many of these contain cave entrances and swallets.

5.4. Somalia.

The gypsum karst of Somalia appears remarkable, both in terms of its extent and the prese of its many and varied karst forms. However, few details have yet been published. Gypsur Eocene age crops out in parts of central and northern Somalia in several areas each larger t $100km^2$. There are many caves, some of which were documented by a Swiss expedition. Thre the larger caves are the maze-like Hyaenenlabyrint cave, with a length of 2,310m and 35m of v cal relief (+8 to -27m), the more linear Bei Las Anodi cave (1,455m, +13 to -10m) and Ail Afv cave (1,275m, +4 to -82m).

A very large gypsum area described by Cecioni (1940, 1944) extends near the town of Galk some way to the south of the above areas. Features include fields of large but shallow dolines plains of white gypsum. A plain surrounds a large collapse doline, about 100m in diameter 60m deep, that is known locally as "The pit of Mullah". The collapse walls overhang in their lc part, and its floor is marshy.

6. Conclusions

Gypsum karst is developed widely throughout the world, though it is more common in northern hemisphere, reflecting the current distribution of gypsiferous formations. It develop all climatological/geographical settings, from cold Arctic to hot arid or humid tropical, from lowermost areas of the Earth's land surface to parts of high mountains. The common belief arid environments are preferred for gypsum karst development is not strictly correct. Altho gypsiferous formations do suffer intense karstification in exposed settings, areas that repre the different development stages of intrastratal gypsum karst are markedly predominant. Gypsum karst is common in deep-seated geological settings, with negligible or no visible expression at the surface. When not only the geomorphological, but also the geological and hydrogeological evidence of karstification in gypsum are taken into account, appreciation of the extent of gypsum karst terrains recognized throughout the world will increase considerably.

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Chapter II.2

GYPSUM KARST IN THE UNITED STATES

Kenneth S. Johnson

Abstract

Gypsum is one of the most soluble of common rocks; it is dissolved readily to form caves, sinkholes, disappearing streams, and other karst features that typically are found in limestones and dolomites. The four basic requirements for gypsum karst to develop are: (1) a deposit of gypsum; (2) water, unsaturated with $CaSO_4$; (3) an outlet for escape of dissolving water; and (4) energy to cause water to flow through the system. Gypsum deposits are present in 32 of the 48 conterminous United States, and they underlie about 35–40% of the land area; they are reported in rocks of every geologic system from the Precambrian through the Quaternary. Gypsum karst is known at least locally (and sometimes quite extensively) in almost all areas underlain by gypsum, and commonly extends down to depths of at least 30 m below the land surface. The most widespread and pronounced examples of gypsum karst are in the Permian basin of southwestern United States, but many other areas also are significant. Human activities may also cause, or accelerate, development of gypsum karst.

Introduction

Evaporite deposits are those sediments that form due to precipitation of various salts out of evaporating water, mainly sea water. Principal evaporite rocks are gypsum (or anhydrite) and salt (halite), although potash salts and other rarer salts also are locally important. (Note: The term gypsum is used in this report, although anhydrite is the common form of calcium sulfate in the deeper subsurface.) Gypsum deposits locally have accumulated to considerable thicknesses, even tens to hundreds of meters thick, where there was continued replenishment of the water from which calcium sulfate was originally precipitated. Thick gypsum deposits are widely distributed in the United States (Fig. 1) and they contain evidence of karst in most areas. Gypsum is one of the most soluble of the common rocks throughout the world, and it is dissolved readily to form the same types of karst features that typically are found in limestones and dolomites. The principal difference is that gypsum-karst features can form rapidly, in a matter of weeks or years, whereas carbonate-karst features typically take years, decades, or centuries to form.

The current chapter provides an overview and summary of the general characteristics and distribution of gypsum karst in the United States. It is based largely upon earlier studies by Quinlan et al. (1986), Dean and Johnson (1989), and Johnson (1997). Other recent comprehensive studies of gypsum in the United States were published by Withington & Jaster (1960), Withington (1962), and Smith et al. (1973). In addition, there are numerous local or regional studies dealing with karst development in the various gypsum deposits: contact with the appropriate

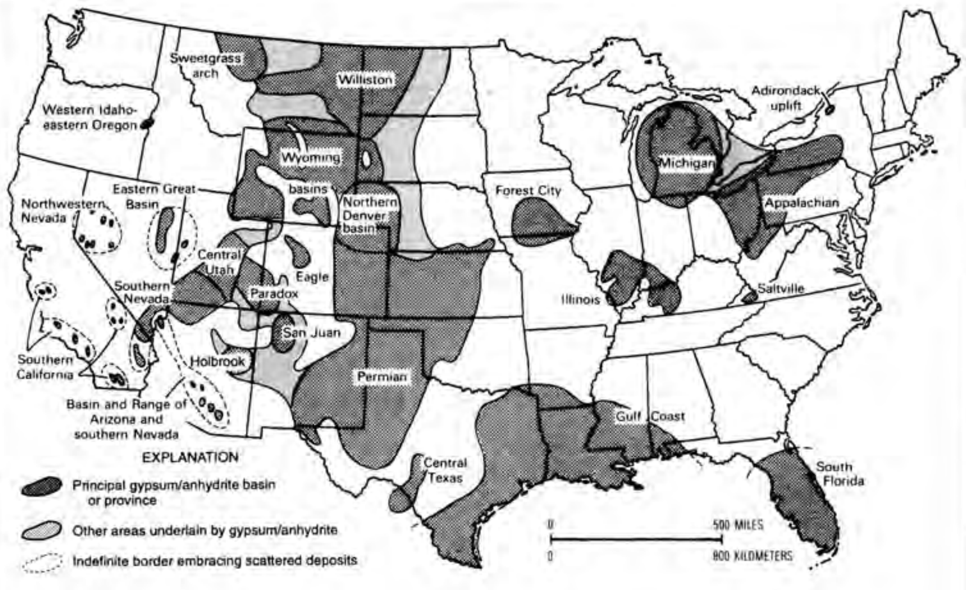

Fig. 1. Gypsum/anhydrite deposits in the conterminous United States (After Dean & Johnson, 1989).

State Geological Survey, and the local cave-exploration groups, is usually the best way to begin a search for such published or unpublished data.

Hundreds of areas or districts in the United States contain karst features that have developed in gypsum rocks, but it is beyond the scope of this summary report to document them all. Therefore, I will discuss the following: (1) the general characteristics of gypsum-karst processes; (2) the general distribution of gypsum karst, and cite several examples that have been well documented; and (3) human-induced gypsum karst that can cause local problems.

Publication of this report is approved by the Director of the Oklahoma Geological Survey.

1. Gypsum karst processes

The processes for development of karst features in gypsum are identical to those that form karst features in limestone and dolomite, except that the processes are much more rapid. Water percolates over or through gypsum and dissolves the highly soluble rock; typically, this causes formation of a series of sinkholes, caves, natural bridges, disappearing streams, and springs. Once a through-flow passage is created in the gypsum, enlargement results from further dissolution and from abrasion, as water-borne particles are transported through the cavity.

The process for dissolution of evaporites was described earlier by Johnson (1981), with particular reference to salt; but it clearly applies to dissolution of gypsum as well. He pointed out that ground water in contact with an evaporite deposit (a gypsum deposit, in the current report) will dissolve some of the rock, providing the water is not already saturated with $CaSO_4$. For extensive dissolution to occur, it is necessary for the aqueous solution thus formed to be removed from the gypsum deposit; otherwise, the water becomes saturated, and the process of dissolution stops. The four basic requirements for dissolution of gypsum are:

(1) a deposit of gypsum against which, or through which, water can flow;

(2) a supply of water unsaturated with $CaSO_4$;

(3) an outlet whereby the resulting gypsiferous water can escape; and

(4) energy (such as a hydrostatic head or density gradient) to cause the flow of water through the system.

When all four of these requirements are met, dissolution of gypsum can be quite rapid, in terms of geologic time.

Gypsum karst is rarely seen at the land surface in eastern United States, but it is fairly common in the semi-arid to arid regions of the west. Owing to rapid dissolution of gypsum, most would-be outcrops in the east are quickly destroyed, and the rock and its dissolution features are observable only in excavations, mines, tunnels, and boreholes. Abrupt thinning or termination of a gypsum deposit, particularly where overlying strata are brecciated, commonly marks a dissolution front (either ancient or modern) where karst processes are, or have been, occurring.

Gypsum karst develops rapidly because gypsum is highly soluble in water. The solubility of $CaSO_4 \cdot 2H_2O$ ranges from about 2,200–2,600 ppm in the temperature range of 0–40°C (Hardie, 1967; Blount and Dickson, 1973). Gypsum-karst development can even be accelerated when accompanied by dedolomitization (Raines & Dewers, 1997). Karst features may be present in gypsum deposits in all parts of the United States, whether the gypsum crops out or is in the deep subsurface; the karst may result from climatic and hydrologic conditions of today, or it may be a relict from an earlier, wetter climate and/or hydrogeologic regime of the Pleistocene or pre-Pleistocene epochs.

In the eastern United States, where average annual precipitation commonly is greater than 75 cm, gypsum deposits generally are eroded or dissolved to depths of at least several meters or tens of meters below the land surface. In the west, however, in areas where the average annual precipitation commonly is less than about 75 cm, gypsum tends to resist erosion and typically caps ridges, mesas, and buttes; in spite of its resistance to erosion in the west, gypsum commonly contains karst features, such as cavities, caves, and sinkholes, attesting the importance of groundwater movement, even in low-rainfall areas.

Evidence of gypsum karst includes surface and shallow-subsurface features, such as caves, sinkholes (dolines), karren, disappearing streams (swallow holes), springs, collapse structures, and the dropping of drill bits and/or loss of drilling fluids while drilling through gypsum beds. All these karst features (Plates 2 & 3), and many more, are identical in character and genesis to those found in carbonate rocks. In fact, paleokarst, becciated zones, and other karst features found in some carbonates may have been initiated by earlier dissolution and karst development in gypsum that is interbedded with the carbonates; Sando (1988), Friedman (1997), and Palmer & Palmer (1997) provide examples and a summary of this carbonate/sulfate relationship. Gypsum-karst features commonly have a linear orientation, and these appear to be controlled by joints or fractures

Plate 1. Cave in Permian Cloud Chief Gypsum in western Oklahoma. Cave opening is about 3 m wide.

in the rock; however, some karst features have a seemingly random orientation, wherein the controls are not understood.

2. Distribution of gypsum karst

Gypsum deposits are present in 32 of the 48 conterminous United States, and they underlie about 35–40 percent of the land area (Fig. 1). Gypsum occurs in 24 separate structural basins or geographic districts in the United States, and is reported in rocks of every geologic system from the Precambrian through the Quaternary. Generally, karst features are present (at least locally) in areas where gypsum crops out, or is less than 30 m below the land surface. The most widespread and pronounced examples of gypsum karst are in the Permian basin of southwestern United States. Other significant examples are in the Illinois basin, Michigan basin, Forest City basin, the Black Hills area of South Dakota, and parts of Texas, Wyoming, and other western states.

The Permian basin contains a thick sequence of Permian gypsum, salt, and red beds that extend from west Texas and southeast New Mexico into western Oklahoma, western Kansas, and southeast Colorado (Fig. 1). Individual gypsum beds typically are 3–10 m thick in most Permian basin formations, but are 20–200 m thick in the Castile Formation of the Delaware basin part of the Permian basin (Dean and Johnson, 1989). Low rainfall in the region permits extensive outcrops of gypsum; particularly in the Delaware basin, to the south, and along the Permian basin's west flank (eastern New Mexico) and east flank (north-central Texas and western Oklahoma). In these

Plate 2. Karst development in Permian Cloud Chief Gypsum in western Oklahoma. Dissolution is most pronounced along joints and bedding planes.

areas, typical gypsum-karst features abound, and are described by Olive (1957), McGregor et al. (1963), Fischer & Hackman (1964), Myers et al. (1969), Kelley (1971), Quinlan (1978), Bozeman et al. (1987), Sares & Wells (1987), Johnson (1990, 1992, 1997), Belski (1992), Hill (1996), and Forbes & Nance (1997). Quinlan et al. (1986) report that there are more than 500 gypsum caves in the United States, and that most of them are in the Permian basin; most of the literature on these caves has been published by local cave-exploration groups.

The Delaware basin of west Texas and southeast New Mexico, in the southwest part of the Permian basin, contains one of the greatest accumulations of evaporites in the United States (Dean & Johnson, 1989). Evaporites (gypsum/anhydrite and salt) of the Late Permian Castile, Salado, and Rustler Formations typically are 500 m to more than 1,500 m thick within the Delaware basin, and are more than 450 m thick where these deposits extend north and east of the basin. Outcrops of these three formations constitute the most extensive examples of gypsum karst in the nation. The area referred to as the Gypsum Plain comprises about 2,600 km^2 of outcropping gypsum of the Castile and Salado Formations (Kirkland & Evans 1980), and additional gypsum outcrops are present just to the east in the Rustler Hills and into Reeves County, Texas.

The Delaware basin gypsum deposits contain abundant sinkholes, caves, closed depressions, collapse sinks, and underground drainage; an excellent summary is provided by Hill (1996). Much of the area has been affected by subsurface dissolution of some of the salt layers, and most of the outcrops consist of massive beds of gypsum. Four principal areas of gypsum karst are Gypsum Plain, Nash Draw, Burton Flat, and the Pecos River Valley (Hill, 1996). Sinkholes, a few meters to 100 m across, are active collapse features in all four areas, and generally they are related to shallow, underground caverns less than 100 m deep. One sinkhole, formed during a storm in 1918, collapsed suddenly to form a gaping hole about 25 m across and 20 m deep (Hill, 1996). Caves are prominent and abundant on Gypsum Plain and Burton Flat (Sares & Wells, 1987; Belski, 1992). The longest gypsum cave in the Delaware basin occurs on Gypsum Plain; Parks Ranch Cave is more than 5,200 m long and it has two sinkhole entrances (Hill, 1996). Other caves in the area are White Horned Owl Cave (about 760 m long) and Skylight and Resurgence Caves (each about 600 m long). Burton Flat consists of more than 275 km^2 of rolling karst plain on which more than 60 caves have been found (Belski, 1992; Hill, 1996); almost all the cave entrances are in gypsum units, although interbedded dolomite beds locally are exposed in the walls of some of the caves.

Along the west flank of the Permian basin, in eastern New Mexico, gypsum crops out extensively along parts of the Pecos River Valley. Various gypsum and carbonate units are present in the Permian Artesia Group, San Andres Formation, and Yeso Formation, and they contain a large number of caves, sinkholes, and other karst features in the Vaughn–Roswell area (Fischer & Hackman, 1964; Kelley, 1971; Forbes and Nance, 1997). Several of the caves in this area are more than 3,200 m long, and the deepest has a vertical extent of more than 120 m (Forbes & Nance, 1997). Individual sinkholes commonly are 7–300 m in diameter, and the larger, coalesced sinkholes are as much as 3–5 km across and up to 60 m deep (Quinlan et al., 1986). Gypsum is preferentially dissolved here by interstratal karstification, and the less-soluble interbeds of carbonates and siliciclastics are thus undermined and now dip down (or drape) toward the center of some of the dolines and subsidence synclines (Fischer & Hackman, 1964). Quinlan et al. (1986) report that Bottomless Lakes State Park, near Roswell, contains the most spectacular group of collapse sinkholes in a gypsum-karst terrane; here, a series of deep, water-filled sinkholes developed in the San Andres Formation as a result of dissolution of gypsum and salt by artesian waters.

Another major gypsum-karst area of the Permian basin is along its east flank, in north-central Texas and western Oklahoma. Principal gypsum units are the Permian Blaine and Cloud Chief Formations, with gypsum beds 3–30 m thick. Among the more important gypsum-karst features of the region are two well-known caves and a major fresh-water aquifer. The J. C. Jester Cave of southwestern Oklahoma (Fig. 4) was surveyed between 1983 and 1987 (Bozeman et al. , 1987; Johnson, 1992); the main passage is 2,413 m long, but, along with the side passages, the total length is 10,065 m, making it the longest reported gypsum cave in the western world. The cave has passageways that typically are 1–5 m in diameter, and locally are up to 20 m wide; it occurs mainly in a 5-m-thick gypsum bed of the Blaine Formation. Alabaster Cavern of northwestern Oklahoma (Fig. 4), now developed as a tourist cave, has a main passage about 700 m long; it has a maximum width of 18 m and a maximum height of 15 m (Myers et al., 1969; Johnson, 1992). The cave is developed mainly in the 10-m-thick, basal gypsum bed of the Blaine Formation. Other gypsum caves are described by McGregor and others (1963), and in various issues of Oklahoma Underground, the journal of the Central Oklahoma Grotto.

A major fresh-water aquifer is developed in the Blaine Formation of southwestern Oklahoma and north-central Texas (Johnson, 1990, 1992). Water is produced from the karstic and cavernous gypsum and dolomite beds of the Blaine aquifer. The aquifer is 50–65 m thick and consists of 9 thick gypsum beds (each 3–8 m thick) interbedded with thinner dolomite beds (0.1–1.5 m thick) and shale beds (0.3–8.0 m thick). Irrigation wells typically are 15–100 m deep and commonly yield 1,000–8,000 L/min. The water is a calcium-sulfate type; total dissolved solids average about 3,100 mg/L (of which about 90% is $CaSO_4$), and the water is suitable for irrigation but generally is unsuitable for drinking.

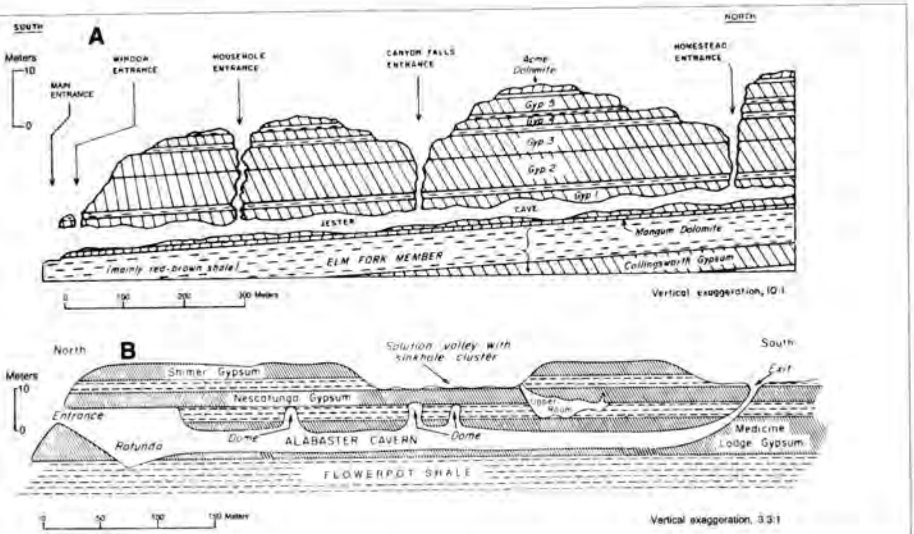

Fig. 2. Schematic cross sections through major gypsum caves in the Permian Blaine Formation of western Oklahoma: (above, A) J. C. Jester Cave; (below, B) Alabaster Cavern. After Myers et al. (1969), Bozeman et al. (1987), and Johnson (1992).

Gypsum karst is indicated, indirectly, along the east and west sides of the Illinois basin in Illinois, Indiana, and Kentucky. The St. Louis Limestone (Late Mississippian) contains several gypsum beds, 1–15 m thick, in the subsurface (McGregor, 1954; Saxby & Lamar, 1957; McGrain & Helton, 1964). Gypsum does not crop out in Indiana and Kentucky, however, because interstratal karstification is dissolving the evaporites and producing ground water with a high concentration of dissolved sulfates along the eastern boundary of the subsurface gypsum deposits (George, 1977). Chemical analyses of springs and well water shows a sulfate concentration of up to 1,350 mg/L, and a low chloride concentration, usually less than 30 mg/L. Westward (downdip) advance of the gypsum-dissolution front in this region generates the sulfate-rich water and collapse of overlying carbonate rocks into cavities. George (1977) cites an example of the collapsed carbonates in Squire Boone Caverns, Harrison County, Indiana. Jorgensen and Carr (1973) show an abrupt lateral thinning of gypsum (from about 4 m thick to <0.5 m thick, within a distance of 150 m) in the St. Louis Limestone near Shoals, Indiana; these authors, along with French and Rooney (1969), ascribe this thinning to dissolution along the eastern, up-dip limit of the gypsum. Saxby and Lamar (1957) also recorded the presence of breccia and the absence of gypsum in outcrops of St. Louis Limestone on the west (Illinois) side of the Illinois basin, and they felt this may have resulted from dissolution of the gypsum.

The Michigan basin contains gypsum karst in the Mississippian Michigan Formation in the central part of the State (Elowski & Ostrander, 1977). The Michigan Formation contains a series of gypsum beds, 1–10 m thick, interbedded with sandstone and shale; these strata crop out locally or are mantled by glacial drift on the east and west side of the basin. Gypsum caves, sinkholes, and collapse features are described in the Grand Rapids area of Kent County (in the west), and also in parts of Iosco and Arenac Counties (in the east) (Elowski & Ostrander, 1977). These authors describe a 100m-long gypsum cavern (Pellerito Cave) that was encountered in an underground gypsum mine near Grand Rapids; the cave is 3–15 m wide and as much as 3 m high.

The Forest City basin area of Iowa contains evidence of gypsum karst in Devonian and Jurassic strata. The Devonian Wapsipinicon and Cedar Valley Groups contain numerous gypsum beds in central and southern Iowa (Witzke & others, 1988). Devonian gypsum does not crop out in Iowa, and it is thought that the present limits of some of the evaporite units are dissolutional; some of the breccia beds (i.e., the Devonian Davenport breccias) are interpreted as having formed by gypsum dissolution and collapse shortly after evaporite deposition (Witzke et al., 1988). The Fort Dodge Formation is an outlier of Jurassic gypsum present in about 40 km^2 of Webster County, central Iowa. The gypsum is as much as 10 m thick, but the upper surface is quite irregular due to partial dissolution before deposition of an overlying Pleistocene till (Cody et al., 1996). This till commonly is 10–30 m thick, but gypsum is exposed locally in stream cuts and quarry faces. The principal karst features are joint-controlled dissolution channels, about 1 m wide and 1–3 m deep, incised into the upper surface of the Fort Dodge gypsum.

Other examples of gypsum karst are noted in central Texas, South Dakota, and Wyoming. The Cretaceous Kirschberg Evaporite Member of the Terrett Formation contains 10 m of gypsum in a quarry near Fredericksburg, Texas (Warren et al., 1990). Vertical pipes, caves, and collapse breccia are well exposed, and gypsum and calcite speleothems (mainly in the form of popcorn and flowstone) were deposited in the pipes and caves. In the Black Hills area of South Dakota, gypsum in the Triassic Spearfish Formation locally contains sinkholes and caves that have caused environmental problems (Rahn & Davis, 1996; Davis & Rahn, 1997). Gypsum beds up to 5 m thick contain sinkholes and caves, and the karst has resulted in general ground subsidence, foundation cracking and seepage in houses, failure of a sewage lagoon, and problems with a proposed mine-tailings facility and a golf-course reservoir. In Wyoming, Sando (1988) describes widespread paleokarst in the Madison Limestone of Mississippian age. He notes that dissolution of gypsum beds within the predominantly limestone sequence during Late Mississippian–Early Pennsylvanian time enhanced contemporaneous development of sinkholes, caves, dissolution-enlarged joints, and breccia zones.

3. Human-induced gypsum karst

Gypsum karst can be accelerated by human activity. Gypsum-karst problems are caused by the same activities that cause problems in carbonate terranes: (1) building structures that induce differential compaction of soils above an irregular gypsum-bedrock surface; (2) building structures directly upon gypsum-collapse features; and (3) impounding water above, or directing water into, a gypsum unit where soil piping can divert water (and soil) into underground gypsum cavities. These human activities can cause land subsidence, or can cause new or concealed sinkholes and cave systems to open up; this can result in settling or catastrophic collapse of the ground.

Specific human activities that have accelerated gypsum karst in the Black Hills area of South

Dakota include (Rahn & Davis, 1996; Davis & Rahn, 1997): (1) sewage lagoons, built on alluvium above a karstic gypsum layer, began leaking badly within one year, and finally failed with partially treated sewage escaping the site; and (2) directing runoff into buried gypsum karst caused several houses to settle and crack, and produced sinkholes in urban/suburban areas. Cooper (1995) also pointed out that (because gypsum dissolution is so rapid) pumping large volumes of gypsiferous water from wells means that subsurface gypsum will be dissolved at an accelerated rate, and this can cause increased subsidence and possible collapse.

Conclusions

This report provides a brief overview of the processes and distribution of gypsum karst in the United States. Caves, sinkholes, disappearing streams, and other features typical of karst terranes are present in gypsum deposits throughout the nation. Gypsum deposits are present in 32 of the 48 conterminous states, and karst is known at least locally in almost all of these areas. Gypsum karst is, in most respects, identical to karst in carbonate rocks, except that the process is much more rapid. It is much more widespread than is commonly believed.

Gypsum karst is most conspicuous in gypsum outcrops, but it also is likely to be found in many areas where the gypsum is up to 30 m below the land surface. The most pronounced areas of gypsum karst are in the Permian basin of southwestern United States, although other important areas include the Michigan, Forest City, and Illinois basins, and parts of Texas, South Dakota, Wyoming, and other western states. Human-induced gypsum karst results chiefly from construction upon, or directing water into or above, outcropping or shallow gypsum deposits.

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Chapter II.3

GYPSUM KARST OF GREAT BRITAIN

Anthony H. Cooper

Abstract

In Great Britain the most spectacular gypsum karst development is in the Zechstein gypsum (late Permian) mainly in north-eastern England. The Midlands of England also has some karst developed in the Triassic gypsum in the vicinity of Nottingham. Along the north-east coast, south of Sunderland, well-developed palaeokarst, with magnificent breccia pipes, was produced by dissolution of Permian gypsum. In north-west England a small gypsum cave system of phreatic origin has been surveyed and recorded. A large actively evolving phreatic gypsum cave system has been postulated beneath the Ripon area on the basis of studies of subsidence and boreholes. The rate of gypsum dissolution here, and the associated collapse lead to difficult civil engineering and construction conditions, which can also be aggravated by water abstraction.

Introduction

Gypsum karst in Great Britain is developed mainly in the Permian gypsum of northern England and, less extensively, in the Triassic gypsum of central England (Fig. 1). Compared with limestone karst it is present in fairly small areas, but rapid dissolution of gypsum produces local subsidence and collapse problems, particularly well displayed around Ripon, North Yorkshire. In addition to the active gypsum karst, gypsum palaeokarst features occur, especially along the coast of north-east England and in the Firth of Forth off eastern Scotland.

1. The active karst in the Permian gypsum of Yorkshire and Durham

Gypsum karst and related subsidence problems occur extensively in the Permian sequence of north eastern England. The belt of gypsum karst is 3-4km wide and extends from just north of Doncaster, through Ripon to Darlington and Hartlepool (Fig. 1). Up to 40m of gypsum is present in the Edlington Formation and 10m in the Roxby Formation (Table). Both these gypsum sequences rest on dolomite aquifers and are capped by marl sequences. However, in the subsidence-prone areas dissolution and collapse are so great that the marls are perforated by subsidence pipes and form very ineffective aquicludes. The Permian sequence is overlain by the Sherwood Sandstone Group a major regional aquifer which is mainly of Triassic age.

The two gypsum sequences of the Edlington and Roxby formations rest on the carbonate aquifers of the Cadeby (or Ford/Raisby in the north) and Brotherton (or Seaham in the north) formations respectively. The carbonate dip slopes act as catchment areas and water is fed down-dip into the gypsiferous sequences. The water escapes into buried valleys, along the River Ure at Ripon (Cooper & Burgess, 1993) and, to a lesser extent, the River Tees near Darlington and the River

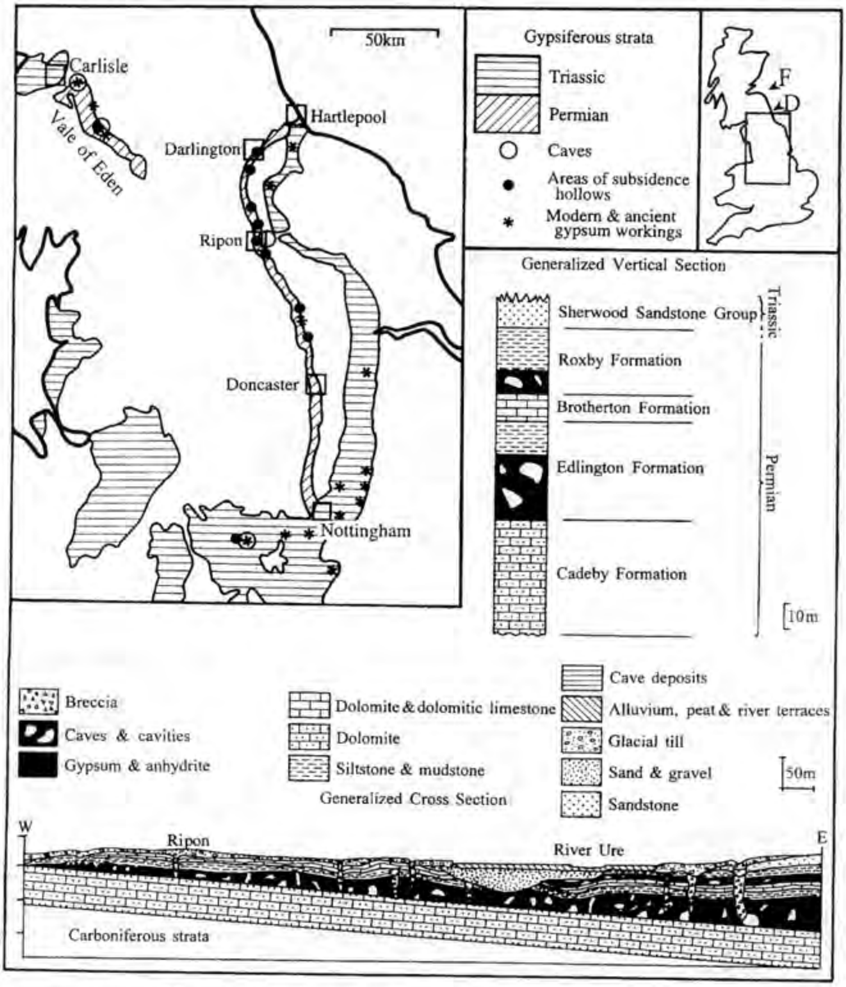

Fig. 1. The distribution of gypsiferous strata in the north of England and the Permian stratigraphical sequence present in Yorkshire. The sketch geological cross-section illustrates the geology in the vicinity of Ripon. The cross-section shows the development of caves in the gypsum sequences and their upward propagation as breccia pipes. Numerous ages of breccia pipes are depicted, some filled in with glacial deposits and others only recently breaking the surface. Other regions mentioned in the text are shown on the inset map of the UK: D - Durham coast area gypsum palaeokarst in Permian sequence; F - Firth of Forth gypsum palaeokarst in the Permian sequence.

Wharfe near Brotherton (50 km SSE of Ripon). Complex cave systems are developed in the gypsum, and artesian sulphate-rich springs are present locally. Because of the thickness of gypsum present the dissolutional voids can be large. At Ripon the dissolution causes surface collapses which occur locally at a rate of about one a year. These collapses can be up to 30m across

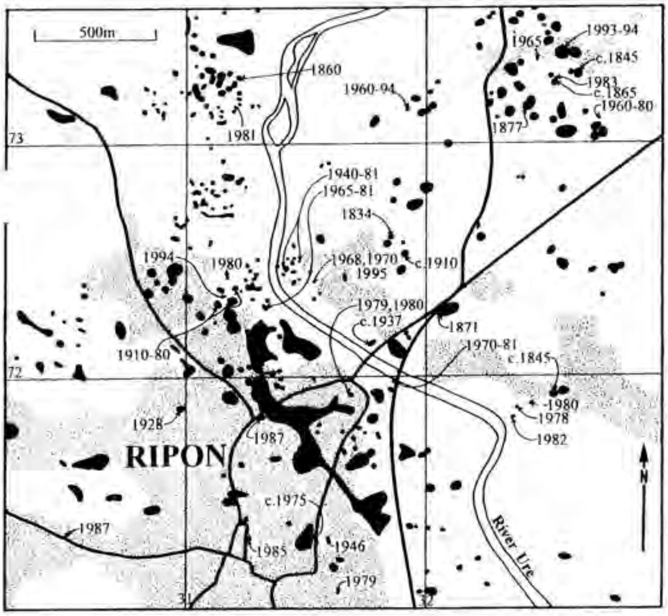

Fig. 2. The distribution and ages of subsidence hollows recorded in the visinity of Ripon, North Yorkshire, UK. The built up areas are shaded and the subsidence hollows and roads are shown in black. The cross-sections in Fig.1 runs approximately SW-NE across this area. The kilometre grig is the National Grig, used with acknowledgement to the Ordonance Survey.

and 20m deep, though most are smaller (Cooper, 1995). The subsidence here is not random, but occurs in a reticulate pattern related to the jointing in the underlying strata (Cooper, 1986, 1989). The distribution of subsidence hollows, and concentration of active subsidence events, show that some zones of subsidence are more active than others. The most active zones are along the margins of the river valley where the groundwater escapes from the gypsum into the Quaternary valley fill and alluvial deposits (Fig.2).

In the east of England the climate is temperate with a strong Atlantic influence and an annual rainfall that ranges from 50 to 75cm. The degree of water infiltration is variable, from very high on bare limestone dip slopes, to low in areas blanketed with thick Quaternary till deposits. Natural dissolution is removing large quantities of gypsum so that the groundwater and many springs are high in sulphate (0.8-2.0g/l). Calculations suggest that the volume of gypsum being dissolved each year at Ripon is about 120m3/km2. The abstraction of groundwater high in sulphates can also remove large volumes of gypsum. Cooper (1988) suggested that at Ripon 200m3 of gypsum was removed each year by boreholes abstracting 212,000m3 of water annually. Much of this dissolution probably represents enlargement of joints, but around the boreholes severe dissolution of the gypsum beds is likely. In addition to dissolution, water abstraction can lower the water table and trigger off both the ingress of Quaternary deposits into the gypsum karst, and the collapse of the cover deposits, resulting in subsidence. Similar problems are suspected of causing subsidence in the Darlington area (Cooper, 1995).

Table

The sequence of the Permian and Triassic rocks in north-eastern England (from Darlington southwards) and their main lithological and hydrological properties.

	Formation/Group	Thickness metres	Description	Hydrological Properties
TRIAS-SIC	Sherwood Sandstone Group	300	Red sandstone with subordinate mudstone beds, especially near base	Major regional aquifer TDS 0.15-0.3g/l mainly as carbonate
PERMIAN	Roxby Formation	up to 26	Red-brown calcareous mudstone (marl) with up to 10m of gypsum (Billingham Anhydrite Formation) at base	Very leaky aquiclude with gypsum karst aquifer at base; sulphate-rich
	Brotherton Formation (Seaham Formation in north)	8-14	Calcitic dolomite, mainly in thin beds	Aquifer TDS~0.5g/l mainly as carbonate; sulphate-rich in places
	Edlington Formation	up to 50	Red-brown calcareous mudstone (marl) with up to 30-40m of gypsum (Hartlepool Anhydrite Formation) at base	Very leaky aquiclude with gypsum karst aquifer at base TDS 0.8-2.0g/l mainly as sulphate
	Cadeby Formation Ford and Raisby formations in north)	up to 65	Dolomitic limestone, commonly massive, but porous and locally leached	Major local aquifer TDS 0.2-0.5g/l as carbonate

2. The karst in the Permian gypsum of Cumbria

In the northwest of England, gypsum of Permian age is well-developed in the faulted half-graben of the Vale of Eden, Cumbria (Figure 1). Four main gypsum sequences are present, named from the bottom upwards as the "A", "B", "C" and "D" beds (Arthurton & Wadge, 1981). The gypsum beds are sandwiched between the mudstone and siltstone aquicludes of the Eden Shales (60-180m thick), except for the basal "A" bed, which rests on the Penrith Sandstone, a local aquifer. The "A" bed is thickest (10m), but is restricted to the south of the Vale of Eden. The "B" bed is the most widespread (4.9-6.6m thick) and present throughout the Vale, extending to Carlisle. The "C" bed (1.2-3.1m thick) and "D" bed (1.2-3.7m thick) occur mainly in the south.

The "B" bed has been widely exploited as a mineral deposit. Gypsum karst features have been noted in many mines and quarries, such as Houtsay Quarry about 30km SSE of Carlisle, where caves were recorded by Ryder and Cooper (1993). Here they noted a downdip transition from west to east from complete dissolution, through buried gypsum karst with gypsum pinnacles to gypsum karst with caves, then into massive gypsum and, in turn, massive anhydrite. The gypsum is sandwiched between low permeability mudstones and the gypsum karst area is around 200-400m wide. A variable sequence, up to 8m thick, of glacial till and sand and gravel with later deposits overlies the gypsum. These deposits conceal and partly fill the buried gypsum karst, suggesting that some of the karst features date from pre- or en-glacial times; the exact climatic conditions that occurred during their formation are unknown. The caves may have partly formed as a sub-glacial phenomenon under increased hydrostatic head. The caves were dry when explored, but this may relate to mining and local de-watering.

The caves at Houtsay Quarry have now been destroyed by quarrying, but approximately 200m of passages were present. In the north there was a single main passage, about 2m in diameter, following an overall south-east to north-west line with frequent changes of size and direction that followed the joint pattern in the rock. In several places there were circular roof pockets and one large aven. At the south of the quarry the caves included two straight tubular phreatic conduits, 1.2-2m in diameter, one with a vertical dissolutional aven that extended through to the top of the gypsum. In all the caves the rock faces were covered by small-scale scalloping. Minor vadose grooves were also present. There were no speleothems, but the gypsum walls commonly had a powdery efflorescence. The cave floors were covered with deposits of ochre-coloured clay, and in the larger caves these were interlayered with peat and broken up by polygonal desiccation cracks. The only other records of caves in the gypsum hereabouts have been given by Rogers (1994) who briefly described caves encountered in the gypsum mines. He noted dry and water-filled avens up to 9m high and 6m in diameter and horizontal passages that ran for more than 18m.

3. The paleokarst in the Permian gypsum of Durham and the Firth of Forth

In the north-east of England, gypsum palaeokarst is well displayed along the Durham coast from Hartlepool northwards to Sunderland. The Permian geological sequence is similar to that in the Ripon area (Figure 2), but with some additional limestone formations in the middle of the sequence. Here the Hartlepool Anhydrite Formation is up to 130m thick and equivalent to the sulphate in the Edlington Formation to the south; it rests on the dolomite of the Ford Formation. In most of the onshore areas the Hartlepool Anhydrite has been completely dissolved, so that the overlying limestones are foundered and perforated by large breccia pipes (Smith, 1994 and numerous references therein). In the coastal cliffs these breccia pipes reach about 30m in diameter and extend upwards for many tens of metres. The area of complete dissolution extends along the coast and eastwards offshore for 3-5km (Smith, 1994, figure 42) passing eastwards into a zone of gypsum karst. The overlying rocks have collapsed and produced a synclinal structure between the old reef front in the west and the dissolution front of the sulphate sequence in the east. The age of the karstification that caused this structure is unknown. Many of the foundered sequences show both massive de-dolomitised collapse breccia and later, more open structured, breccia-filled pipes. Smith (1994) considers that some of the dissolution was initiated during Mesozoic earth movements and uplift. The intrusion of an igneous dyke (dated at around 58 million years) into collapse breccia at Whitburn suggests that uplift and dissolution had commenced by the mid-Paleocene. In many places the only relics of the gypsum and anhydrite sequences are dissolution residues of heavy mineralrich clays.

Beneath the seabed of the Firth of Forth and North Sea (about 90km east of Edinburgh) the late Permian sequence crops out beneath Quaternary deposits commonly 10-20m thick. Gypsum and anhydrite have been proved in shallow boreholes and the surface of the rock has been imaged by shallow seismic surveys (Thomson, 1978). These investigations prove a gypsum karst surface with pinnacles of gypsum and anhydrite surrounded by foundered strata. This foundering affects strata including the overlying Triassic sandstones. The belt of foundered strata and sulphate karst is 10 to 20km wide. In the west, anhydrite and gypsum have been proved, but in the east a dissolution residue was tentatively recognised. The age of this karst is not known, but may be similar to the offshore sulphate karst of Durham.

4. The karst in the Triassic gypsum of Central England

Around Nottingham (Figure 1) gypsum has been exploited at two main levels in the siltstones and mudstones of the Triassic Mercia Mudstone Group; these are the Tutbury and Newark gypsum beds. The Tutbury Gypsum is massive, up to 8m thick, and the Newark Gypsum comprises an 18m sequence of mainly nodular and thinly bedded gypsum with mudstone. In the Tutbury Gypsum mined at Fauld (40km WSW of Nottingham), Wynne (1906) recorded areas of dissolution and collapse including a "circular wash hole"; this appears from his description to be a phreatic tube about 6m wide and 2m high. Nearby at Chellaston (Smith, 1918) described the sequence as having numerous swallowholes adjacent to pillars of gypsum; he also described the pinnacled upper surface of the gypsum and gypsum breccias, all features typical of gypsum karst.

In addition to the Tutbury and Newark gypsum, the mineral is also present in much of the associated Triassic sequence. The widespread dissolution of gypsum in these rocks of the Nottingham area was recorded by Elliott (1961), who noted a near-surface zone (0-30m) with cavities and brecciated strata where most of the gypsum had been dissolved. Recent exposures for a new road have shown that the Tutbury Gypsum of the Aston upon Trent area (20km SW of Nottingham) caps the hills, where it has been extensively mined. On the sides of the hills the gypsum passes downdip, towards the water table, into a zone of partial dissolution with collapse areas and cavities. It then passes into an area of severe dissolution with only relict masses of gypsum up to 5m across, and finally into a zone of complete dissolution. In the areas where dissolution has been severe the foundered mudstones are weak and give rise to difficult engineering conditions for road and bridge construction.

5. Environmental problems associated with gypsum karst

Subsidence is the most common environmental problem associated with gypsum karst in the UK. Sudden catastrophic subsidence occurs around Ripon about once a year and has resulted in damage of about $1,500,000 in the last 10 years. In the city of Darlington large areas of housing have also been damaged. Amelioration of the subsidence problems can be approached on two fronts: planning and construction.

A recent study of the Ripon problem has recommended a formal approach to planning for gypsum geohazards (Thomson et al, 1996). This involves recognising the subsidence-prone areas and having guidelines for site investigation, design and construction. For each planning application special proformas have to be signed by a "competent person" who is a qualified geotechnical specialist. The most cost-effective way of developing gypsum karst areas is to avoid the subsidence problems by keeping development away from actively subsiding areas, subsidence hollows and areas between subsidence hollows. If these areas cannot be completely avoided, development might be possible after a full site investigation has been undertaken. Some areas of subsidence have been close to or connected with water abstraction (Cooper, 1988). Integral with the planning, careful consideration should be given to the restriction of water abstraction in gypsum karst areas, both to reduce the amount of gypsum dissolution and prevent drawdown of the water table which can trigger subsidence.

For construction, site investigation can be made more cost-effective by the use of geophysical techniques, especially microgravity (Patterson et al, 1995) and resistivity tomography (Cooper, 1995). Development may then proceed by using reinforced and extended foundation structures for buildings, and geogrid textile materials for the protection of roads (Paukstys et al, in press). At Ripon a specially reinforced bridge has been constructed with sacrificial piers, so that the collapse of any one support will not cause the bridge to collapse; the structure has also been equipped with load monitoring devices to warn of any failure.

Acknowledgements

My thanks are given to my many previous co-authors who have helped with the work summarised here. Special thanks go to Dr D.Holliday for informing me about the Firth of Forth gypsum karst and Dr D.B.Smith for discussions about the Durham coastal karst features. Mr T.J.Charsley and Dr. D.J.Lowe are thanked for critically reviewing the manuscript. This paper is published with permission of the Director, British Geological Survey (N.E.R.C.).

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Chapter II.4

GYPSUM KARST OF FRANCE

Michel Chardon & Jean Nicod

Many small and scattered areas of gypsum karst are present in France. They occur in the plains and plateaux (Paris, Lorraine, Provence) as well as in the mountains, especially the Alps (Fig. 1). Typical gypsum karst landforms are well developed and widespread, but underground cavities are scarce, despite much exploration and the apparent existence of subsurface waterflow. The Alps and Provence contain the largest karstic areas.

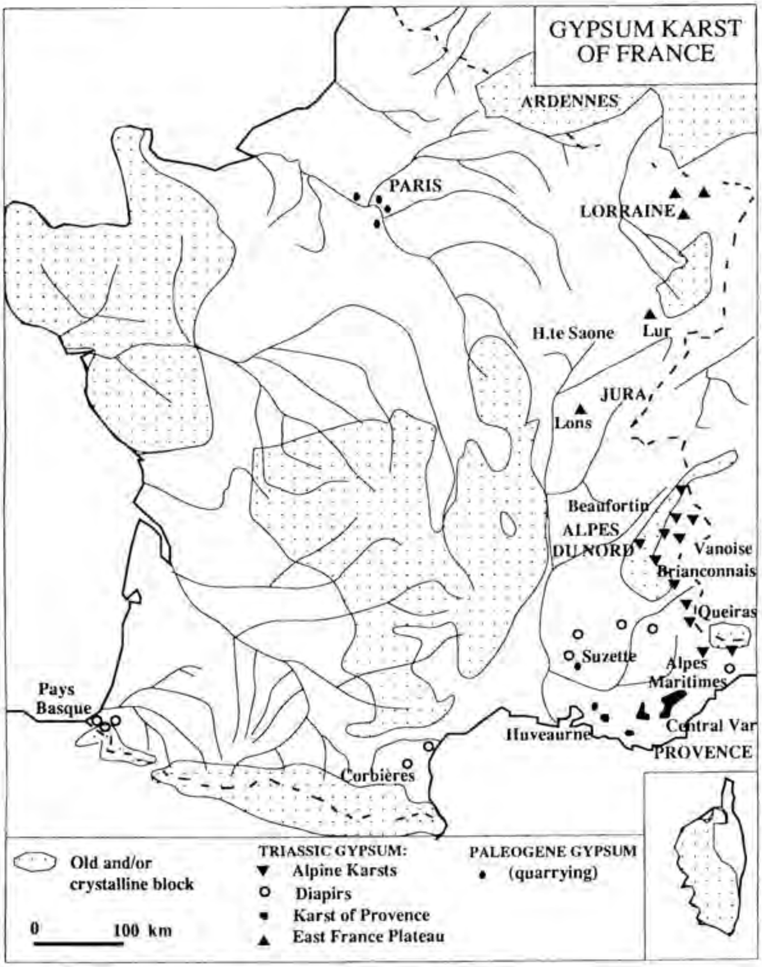

Fig. 1. Gypsum karst in France (After Karstologia 25, 1995).

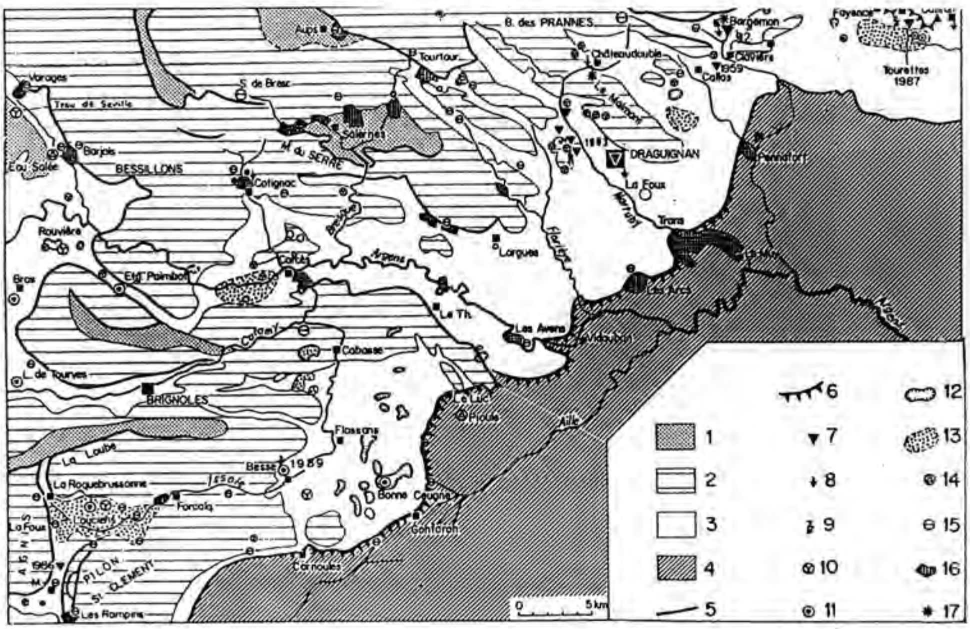

Fig. 3. Karst phenomena and landslides in gypsum karst of the Middle Var (Provence). 1 = late Cretaceous and Cenozoic basins, 2 = Jurassic limestone plateaux, 3 = Triassic, 4 = Permian depressions, 5 = main tectonic scarp, 6 = cuesta, 7 = funnel or "clape", 8 = collapse, 9 = landslide, 10 = doline, 11 = karst lake, 12 = uvala, 13 = filled polje, 14 = sulphate spring, 15 = other springs, 16 = travertines, 17 = old gypsum quarry.

At the centre of the Var district, a multi-bedded gypsum aquifer is fed by water leaking down from the overlying karstified Jurassic limestones; in the Issole valley various karstic ponds and lakes are related to this hydrological phenomenon. Many springs hereabouts have sulphate and chloride waters, such as La Foux de Roquebrussane in the Nartuby valley, which is the main spring feeding the ponds and lakes. It has the following characteristics: mean discharge 0,9m^3/s, mean ionic composition (in meq./L): Ca^{2+} =20.6; Mg^{2+} =2.8; SO_4^{2-} =15.1; Cl^- and Na^+ =13; the total solute load = 27,265m^3/year. This active chemical corrosion is responsible for the development of numerous superficial karstic landforms.

No important caves have been noted around here, but from time to time superficial collapse pits suddenly appear, due to breakdown of underground cavities. They include the "clapes" (funnels) in the Naturby valley, just above Draguignan; of these "La Nouvelle Clape" formed in 1983 and "Le Trou de Bargemon" (about 40,000m^3 in volume) formed during August of 1992. Ponds or lakes (Grand Lucien, Besse) are located on the anticlinal structures of the Muschelkalk limestones, they are situated in collapse sinkholes formed by the dissolution of the underlying gypsum beds. Some of the flat-floored dolines have a thick colluvial cover along their slopes and small poljes such as Marais de Gavoty, with siliceous deposits, can be interpreted as having had a long evolution, possibly since the Late Miocene.

3. Other important areas of Triassic gypsum

Some large karst landforms are known in the Alpes Maritimes, North of Nice. These include the enormous sinkhole of Beuil-Valberg and the 200m-long cave of Source des Isles in Lantosque. The massive Roquebilliere landslide, which occurred here in 1926, has also been attributed to gypsum dissolution after heavy rain.

In the Western Pyrénées, karst depressions are connected with Triassic gypsum that occurs in diapiric structures, the most conspicuous is Bassin de Sare in the Basque country.

In the eastern part of France, Loraine and Franche-Comté, there are many landforms resulting from collapse, including funnels, pit holes and sinkholes or "mardelles", which occur commonly in the forest areas. However, La "Font de Lure" in Haute Savoie is a sinkhole pond in the central part of the town.

Tertiary gypsum beds (Palaeocene and Ludien) are well-known in the central part of the Paris sedimentary basin; at Forêt de Montmorency they are up to 30m thick. Hereabouts many natural caves have been encountered in both ancient and modern mines. The old gypsum quarries of Vaulours and Béthemont-en-Forêt lead to a 350m-long cave network called Denis Parisis. The surface karst landscape above the gypsum is dotted by numerous collapse sinkholes, of which the best example is Chanteloup-les-Vignes.

4. Environmental and geotechnical problems

Numerous natural hazards and risks have been associated with gypsum karst processes and landforms. These processes can be accelerated by climatic variations and human impact, including amongst others, dam construction and water abstraction.

Many collapse phenomena have allowed the delineation of potentially dangerous areas in Provence. These include the centre of Draguignan, districts of Bargemon, Callian and Abbaye du Thoronet, plus Roquevaire, where the old gypsum quarries are now deserted. In the Paris district many events, reported as "fontis" or breakdowns, have occurred in Meudon, Aubervilliers, Montreuil, Chanteloup and Porte de la Chapelle. The same phenomena have been noticed in the Alps at Grand-Coeur and Aussois.

Landslides, torrential floods and mud flows are also more common where gypsum crops out, especially in the Alps: Tarentaise (Pralognan, Moutiers); Maurienne (Modane, Val Cenis); Alpes Maritimes, Beaufortin (Aréches).

These natural hazards are allowed for by geotechnical mapping and prediction. Z.E.R.M.O.S. maps and "Cartes et Plans de Prévision des Risques Naturels" (P.E.R.) have been compiled for many of the potentially dangerous zones. In the Paris Basin the collapse risk is increased by over pumping water from the underlying aquifers. In the Alps, where there is a lack of surface water flow, the contamination of drinking water supplied from springs is a serious problem for some important tourist centres and ski-resorts, such as La Plagne, Tignes and La Norma. Human activity has caused a severe increase in the rate of karstic denudation, slope gullying, landslides and the sudden formation of subsidence pits. Many problems have been caused by civil engineering projects, including the construction of roads, artificial ski paths and artificial tunnels, which have destroyed the natural morphological balance of the landscape in areas such as Val Fréjus, La Plagne, Tignes, Galibier and Modane.

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Chapter II.5

GYPSUM KARST OF GERMANY

Stephan Kempe

1. Geological Situation

After the Variscan Orogeny, the larger section of Germany became part of the European continent. However, continued subsidence and rifting provided basins, which where occupied by epicontinental, i.e. relatively shallow marginal seas. Because of the low paleo-latitude of these basins, evaporation caused desiccation of these inland seas and the deposition of salt, gypsum and carbonates. Salt or gypsum were deposited in the Permian, Triassic and Jurassic (Richter-Bernburg, 1955a). Upon burial, the gypsum quickly was converted to anhydrite and is only converted back after having been exhumed almost completely so that often only the upper meters of a sulfate formation are gypsified.

The lower Permian (Rotliegend) salt and gypsum basin of the southern North Sea, which extends eastward toward Poland, is apparently not responsible for any specific karst development. The upper Permian (Zechstein) basin is much larger; it streches from England through the North Sea, across Northern and Eastern Germany far into Poland. A bay reached southward: the Hessian Depression. The geology and stratigraphy of the German Zechstein basin was extensively reviewed by Kulick & Paul (eds., 1987). In the north, up to eight salinar cycles can be differentiated, but only the lowest three (Werra Series, Staßfurt Series, Leine Series) can be traced at the surface (Richter-Bernburg, 1955b). The cycles typically start with a claystone, continue with a few meters of a limestone or dolomite, grade into massive anhydrite formations and finish with very thick halite and potash deposits. The gypsum formations are the Werra Anhydrite (A1), Basalanhydrite/Sangerhäuser Anhydrite (A2), and Hauptanhydrite (A3), which are the most important karst-bearing sulfate formations in Germany. Furthermore the upper Buntsandstein (lower Triassic; abbriviated So; 1 to 3 layers), the middle Muschelkalk (middle Triassic; abbrivated Mm; 1 layer), the middle Keuper (upper Triassic, abbrivated Km; Gipskeuper, 1 layer), and the upper Jurassic (Münder Mergel, 1 to 4 layers) occur near enough to the surface to give rise to karstic features (Herrmann, 1964).

Because of the wide extend of the Zechstein Basin (Fig. 1) and the enormous amount of salt deposited (the Staßfurt salt reaches 600 m), much of Northern Germany is underlain by salt domes. These provide the main tectonic structures in northern, north-central and eastern Germany, uplifting and tilting the sediments of the younger formations and punctuating even Pleistocene sediments. In Segeberg, Stade, Elmshorn and Lüneburg, for example, gypsum is found very near the surface or even rising in conspicuous hills above the moraines of the Last Glacial (in Segeberg).

To the south, mountain ranges consisting of folded Variscan rocks were uplifted as a reaction to the Tertiary Alpine Orogeny. These mountain ranges, Harz, Kyffhäuser, Rheinisches

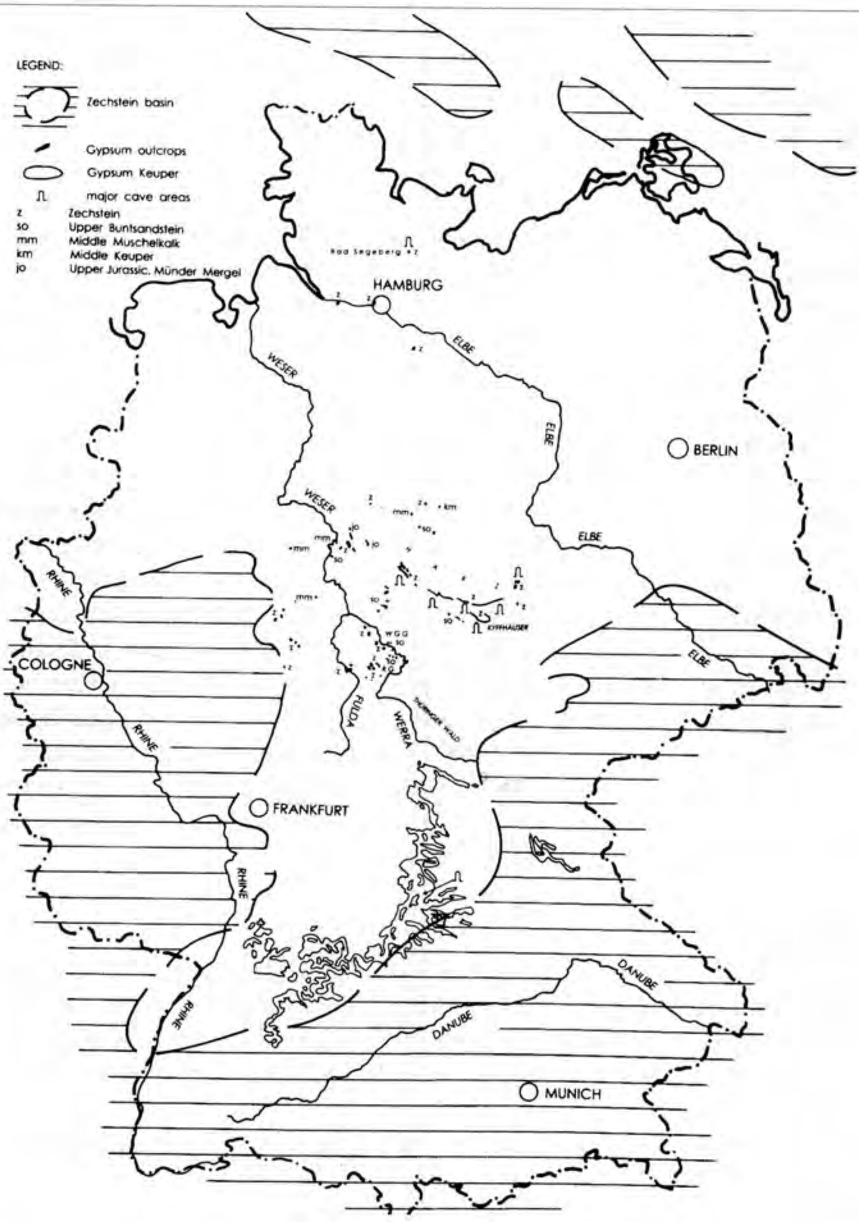

Fig. 1: Geological map of Germany with gypsum karst areas, compiled from various sources (e.g., Herrmann, 1964, 1976, and geological maps). RG = Richelsdorfer Gebirge; WGG = Werra Grauwacken Gebirge."

Schiefergebirge, Thüringer Wald, Richelsdorfer Gebirge and Werra-Grauwacken Gebirge, are fringed by Zechstein outcrops. The areas south of the Harz and Kyffhäuser are the largest continuous gypsum karst areas found in Germany. The outcrops actually belong to two different basins, separated by an old Variscan High, the Eichsfeldschwelle (part of the Hunsrück-Oberharz High), situated between Herzberg and Osterhagen (Herrmann, 1956; Jordan, 1979). On top of this NE-SW-striking High, evaporation of seawater was especially intense and large amounts of gypsum precipitated. It was transported into the adjacent basins. During the Werra Series the eastern basin was filled with more than 300 m and the western basin with more than 200 m of gypsum (the so-called "gypsum walls"). In the upper Staßfurt the Eichsfeld High become flooded and the relatively thin (up to 25 m) Basalanhydrite extends across it. In the eastern basin the Basalanhydrite is followed by the Sangerhäuser Anhydrite, itself ca. 40 m thick. The Leine Series gypsum (Hauptanhydrite) was deposited throughout the basins with a thickness of up to 50 m.

In between and to the south of theses mountain ranges isolated and very often tectonically disturbed outcrops of Zechstein, So, Mm and Km occur, most of them due to salt dome tectonics. Münder Mergel only occurs in a very local area, the Hils anticline. Only a few, very small caves have been described from these areas (Stolberg, 1934, in the So of the Hainleite range; Fischer, 1973, and Kasch, 1986, also in the So at Jena; Wrede, 1976, in the Zechstein of Othfresen, Salzgitter, caves mapped by Kempe; in the Mm of the Hopfenbergtunnel near Kreiensen, inaccessible now, cave mapped by Reinboth, unpublished). Towards southern Germany, in Bavaria and Baden Württemberg, the Mesozoic formations dip gently south towards the Tertiary Alpine Molasse Trough and an escarpment-dominated landscape formed, interrupted locally by minor tectonic horst and graben structures. Here the So, Mm and Km gypsum underlay large areas. The only cave area of note occurs near Markt Nordheim (Götz, 1979). Herrmann (pers. com.) reported of some caves in the gypsum mine (Km) near Seinsheim, the longest measured 150 m (map by Reinboth, unpublished). They are inaccessible now.

2. Gypsum Karst

$CaSO_4$ is highly soluble; about 14 mmol/l dissolve at 10°C (Wigley, 1973), i.e. 2.4 g of gypsum ($CaSO_4*2H_2O$; density 2.3g/cm^3) or 1.9 g of anhydrite ($CaSO_4$; density 3.1 g/cm^3) per liter. Brandt et al. (1976) and Kempe et al. (quoted in Kempe, 1982) measured gypsum karst springs in the Hainholz and found annual averages of 13.5 (Jettenquelle) and 14.0 (Schurfquelle) mmol/l $CaSO_4$ (2.3 and 2.4 g gypsum/l).

Weighting the specific discharges of Elbe, Weser and Rhine by their respective tributary areas (data compiled in Kempe et al., 1981) an average runoff (i.e. the difference between precipitation and evapotranspiration) of 323 mm/a can be assumed for Central Europe. This amount of water could dissolve gypsum at a rate of 0.036 cm/a (0.021 cm/a for anhydrite), consuming a 10 m thick layer of gypsum within 28,000 a (48,000 a for 10 m of anhydrite). For the Hainholz, a runoff of 450 mm/a was calculated resulting in a karstification rate of 0.044 cm/a (Brandt et al., 1976).

Under such conditions, it is actually astonishing that open gypsum karst exists at all in Central Europe. Several factors assist in the continued existence of these areas and determine their development. These are the Glacial-Interglacial climate cycles and the tectonic situation, which determines local hydrology and geomorphology.

In Glacial times, much of northern Germany was overridden by Scandinavian glaciers. The non-glaciated areas were subjected to harsh periglacial conditions. Permafrost effectively blocked groundwater formation and subsurface runoff for extended periods of time. This is well documented in limestone caves (Kempe, 1989). There, sinter grew only during the short Interglacials while it was mechanically destroyed by cave ice during the Glacials. Under permafrost dissolution of gypsum dropped to a minimum and its denudation was more by erosion than by corrosion. Evidence of periglacial erosion of gypsum is found all along the South-Harz where the gypsum karst is crossed by dry valleys. These valleys were once linked to Harz rivers which now either sink when they reach the gypsum or are deflected into subsequent depressions to join one of the few deep valleys funnelling Harz rivers through the Zechstein barrier. These consequent valleys, including the Söse, Sieber, Oder, Steina/Ichte, Uffe, Wieda, Salza, Thyra, Nasse, and Leine valleys (from W to E), mostly follow tectonic structures. But even these larger rivers seasonally loose part or all of their water, while crossing the Zechstein (Haase, 1936). This water reappears in some of the

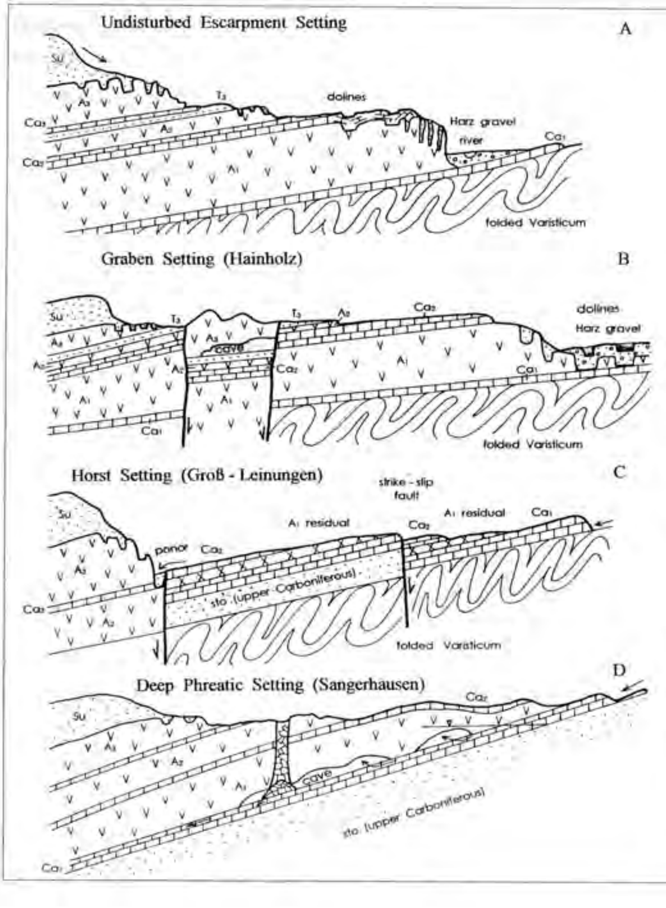

Fig. 2: Schematic cross-sections of the Zechstein karst of the S-Harz, a) tectonically undisturbed escarpment karst, b) karst area developing in a tectonic graben, example Hainholz, near Düna/Osterode, Niedersachsen, c) karst development along strike-slip faults causing a horst situation near Groß Leinungen, Sachsen-Anhalt, d) scheme of the deep phreatic karstification in the Sangerhausen and Mansfeld mining area, Sachsen-Anhalt.

most spectacular karstic springs of Germany, such as the Rhumequelle (Herrmann, 1969b), and the Salza Spring (Haase, 1936; Kupetz & Brust, 1994), kilometers below their points of infiltration. Along the Thyra near Uftrungen, sinking water undermining the western flank of the valley has created one of the largest gypsum cave systems in Germany, the Heimkehle (Völker, 1981).

It is interesting to note that most of the dry valleys have apparently been disconnected from their respective Harz rivers since well before the last Glacial. This is evident from the lack of Harz gravel in these valleys, which must have been removed under permafrost itself. Only pockets of Harz gravels remain (for example in the Marthahöhle, Hainholz), suggesting that these valleys date into the Elsterian Glacial (Brandt et al., 1975) and that the subsequent valleys have developed since, i.e. in the last three Interglacials. German gypsum karst therefore develops intermittently and experienced karstification stasis during Glacials and rapid development during Interglacials.

The tectonic situation also plays an important role in determining the type of karst. Along the South Harz, the formations dip 10-15° to the SW (Jordan, 1979). Where they are tectonically undisturbed, the A1, A2 and A3 form a set of three escarpments topped by the escarpment of the lower Buntsandstein (Priesnitz, 1969, 1972; Herrmann, 1969a, 1981b; Fig. 2a). The A1-escarpment is the most prominent, not only because the A1 is the thickest formation but also because it is often undermined by rivers following subsequent courses (near Osterode, for example) or sinking streams (at the Trogstein near Bad Sachsa, for example).

Due to the relatively fast recession of the A1 face not many karst features can develop at the main escarpment. In quarries mostly deep circular karren are noticed, up to 30 m deep (termed geologische Orgeln or Schlotten in German) and filled with slumped clay and limestone from the overlaying Staßfurt Series. The Staßfurt carbonates also form a prominent plateau above the A1 face where shallow dolines occur. The A2 escarpment is missing in most places because of the low thickness of this formation while the A3 escarpment is often masked by slumped lower Buntsandstein (abbriviated Su). However, the Su provides runoff which causes the extensive formation of dolines and small ponors filled with red Buntsandstein mud. Several kilometers south, beyond the Su-escarpment, is a wide valley, this is the depression caused by the dissolution of the Zechstein salt more than a hundred meters below the surface.

In this sort of undisturbed tectonic setting, karst develops only along the very narrow bands of gypsum outcrops. Larger karst areas occur only where the gypsum is protected from erosion tectonically. This is, for example, the case in the Hainholz Nature Preserve near Osterode (Fig. 2b). Here the A3 was downfaulted and forms a graben, which protected the Hauptanhydrite from erosion under permafrost conditions. The Su was simply stripped off and a relatively large area of gypsum was uncovered. The park features 39 hectares of fully developed karst (Kempe et al., 1972; Brandt et al., 1976; Kempe et al., 1976; Herrmann, 1981a; Jordan, 1981; Vladi, 1981) including sinks, karstic springs and extensive active cave systems (over 30 objects listed) which led to a series of spectacular collapse holes (Erdfälle in German). Weinberg (1981) has documented the fast evolution of one of these sinkholes since the last Interglacial. In addition, countless circular karren are developed. They are filled with marl, which was partly excavated in the past in order to ameliorate nearby fields. In 1751, this marl exploitation yielded the first bones of the extinct wooly rhinoceros ever described (Vladi, 1979). Archeological excavations suggested that the natural pits

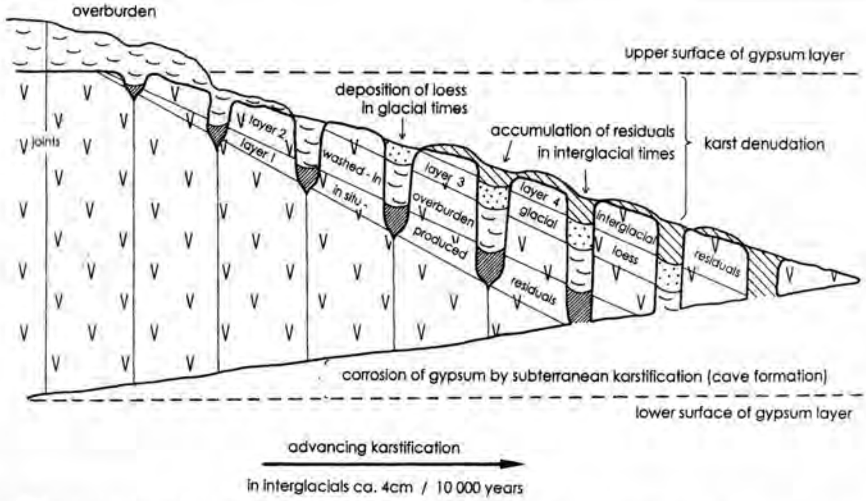

Fig. 3: Development of circular karren (Kempe & Emeis, 1979) according to sediment sampling conducted during archaeological excavations (Grote, 1979) in the Hainholz, Düna/Osterode, Lower Saxony.

may have been used by paleolithic hunters to trap animals (Grote, 1979). Fig. 3 shows how the sediment of these pits may have formed and how these pits keep ahead of the general lowering of the surface (Kempe & Emeis, 1979, 1981).

Several other areas have similar tectonic settings, like the Trogstein/Weißensee/Nuxei karst near Tettenborn and the Himmelreich near Walkenried, both also well known for their sinks, springs and caves (Priesnitz, 1969; Reinboth, 1963, 1969, 1970; Stolberg, 1928, 1932).

Further to the east, prominent E-W trending strike-slip faults with small amounts of uplift or downthrust have structured the area. Along these faults creek and groundwater flow is diverted into subsequent directions, creating an extensive, prominent strike valley (Auslaugungstal). Thereby, the escarpments of the higher Zechstein are protected from corrosion. The water infiltrates into the A1 as is the case at the Dinsterbachschwinde near Questenberg, but often the lower Zechstein is completely missing, only residual limestones remaining at the surface (Fig. 2c). In these cases Harz waters can collect and infiltrate the A3 directly such as is the case at the Bauerngraben, a spectacular episodic ponor-lake (Völker & Völker, 1983) and at the Ankenbergschwinde near Groß Leinungen, all in Sachsen-Anhalt.

In southern Germany the gypsum layers of the So, Mm and Km are less steeply inclined, their bedding lies almost horizontally (Herrmann, 1976). They are less thick and their fronts have been deeply corroded. Therefore they do not form prominent escarpments and rarely break the surface. Exceptions occur near Markt Nordheim, Franken/Bavaria, where also caves have developed in the Km, which occurs near the surface (Götz, 1979).

3. Gypsum Caves

German gypsum caves have been a subject of study since several centuries. The earliest account of a gypsum cave is that of the Kelle, near Ellrich, which was described by H. Eckstorm in 1597 (Reinboth, 1989, 1996). Georg Henning Behrens (1703) mentioned, in the first review about Harz caves, entitled "Hercynia Curiosa", already seven gypsum caves (among them the Heimkehle and the Kelle). At the same time caves were encountered incidentally or on purpose in the eastern Harz in the mining districts of Sangerhausen and Mansfeld during the early days of modern mining. The mined vein is the Kupferschiefer, the 10 to 60 cm thick claystone forming the base of the Werra (A1) Series. It is impregnated with several percent of copper and other metal sulfides. As the miners followed the formation deeper and deeper underneath the A1-escarpment they encountered severe water problems. They soon learned that water could be piped into so-called "Schlotten" (Kupetz & Brust, 1991) (not to be confused with the circular pits at the karst surface), enormous underground cavities formed along the paths of sinking water (Fig. 2d). The vaults were also handy when it came to deposit mine wastes. The ownership of such a cave could decide about success or failure of the mine venture. Thousands of pages dealing with these caves and the law suites about their ownership still exist (Korte et al., 1982; Völker & Völker, 1983). Around 1799, the largest of these caves, the Wimmelburger Schlotten, were discovered (Fig. 4) (Völker & Völker, 1986). Freiesleben (1809) published the first scientitific paper about these caves, including maps, in which he already suggested that they form in standing water. Altogether he mentioned almost 30 Schlotten and other caves in gypsum.

It then took over a hundred years before somebody else addressed the question of how these caves were formed and where the water eventually ended up (Fulda, 1912, unpublished). In 1913, when in Segeberg, Schleswig-Holstein, a large cave system was found by quarrying (see Table 1), Karl Gripp (1913) started the modern scientific gypsum cave research. The cave has a maze-like pattern, rather flat ceilings and peculiarly inward sloping side walls (Fig. 5). Gripp concluded that the cave has been formed by very slow solution in a more or less standing water body. He also postulated that the side walls would start vertically and then tilt outward as solution continued. In 1926, Friedrich Stolberg published a review of all the accessible gypsum caves in the Harz and included newly surveyed maps. With Stolberg's maps and Gripp's theories at hand Walter Biese (1931) reviewed the gypsum cave development and firmly established the concept of the solution cave (Laughöhle), which is characterized by flat ceilings and sloping side walls (for which he introduced the terms "Laugdecke" and "Facette", respectively). He also showed that the Schlotten-type caves are solution caves as well.

In West Germany Fritz Reinboth (1968, 1971b, 1974, 1992) and the author (Kempe, 1969, 1970, 1972a,b, 1975; Kempe et al., 1975, Kempe & Seeger, 1972; Brandt et al., 1976) developed the theory of gypsum cave evolution further, while in East Germany the practical exploration of caves was the main thrust, until in the 1980ies Völker & Völker began their publication series on gypsum karst, caves and schlotten. After the reunification of Germany the first field guide, covering both sides of the South Harz karst, appeared (Kupetz & Brust, eds., 1994) and now a hiking path leads along the entire expansion of the South Harz karst landscape (Völker & Völker, 1996).

Table 1

List of German gypsum caves longer than 200 m

1. Wimmelburger Schlotte**	Wimmelburg, E-Harz, Sachsen-Anhalt; large, deep phreatic solution cave system (Biese, 1931; Stolberg, 1943; Völker & Völker, 1986)	2550 m
2. Segeberger Kalkhöhle*	Bad Segeberg, Schleswig-Holstein; maze type, drained, shallow phreatic solution cave with some breakdown halls (Gripp, 1913; new survey, including all side passages, Fricke, 1989)	1985 m
3. Heimkehle*	Uftrungen, S-Harz, Sachsen-Anhalt; shallow phreatic solution cave with breakdown-dominated large halls (Stolberg, 1926; Biese, 1931; Völker, 1981)	1780 m
4. Numburg-höhle***	Kelbra, Kyffhäuser, Sachsen-Anhalt very large, shallow phreatic solution cave with enourmous breakdown halls (Stolberg, 1926; Völker, 1989; Völker & Völker, 1991)	1750 m
5. Schlotte am Ottilaeschacht****	Ahlsdorf, Sachsen-Anhalt; large, deep phreatic solution cave (Stolberg, 1943)	1710 m
6. Höllern**	Markt Nordheim, Franken, Bavaria; maze type, active, low, shallow phreatic solution cave (Cramer & Heller, 1933; Götz, 1979)	1040 m
7. Jettenhöhle	Hainholz, S-Harz, Niedersachsen; active, shallow phreatic solution cave with large breakdown halls (increased by 130 m since 1990), (Stolberg, 1926; Kempe et al., 1972)	748 m
8. Schlotte am Schacht E****	Mansfeld, E-Harz, Sachsen-Anhalt; large, deep phreatic cave (Stolberg, 1943)	725 m
9. Barbarossahöhle*	Rottleben, Kyffhäuser, Thüringen; shallow phreatic solution cave in anhydrite, dominated by vaulted halls(Biese, 1923; Kupetz & Mucke, 1989; Kupetz & Brust, eds., 1994)	670 m
10. Himmelreich-höhle**	Walkenried, S-Harz, Niedersachsen; possibly formed by creek down-cutting, one very large hall with stream passages (Biese, 1931; Reinboth, 1970)	580 m
11. Niedersachsen	Fitzmühlen Quellhöhle Tettenborn, S-Harz; low, vadose stream cave (Haase, 1936; map by A. Hartwig, 1988, unpublished)	545 m
12. Brandschächter Schlotte****	Sangerhausen, S-Harz, Sachsen-Anhalt; deep phreatic solution cave (Stolberg, 1943; Völker, R., 1983)	530 m
13. Marthahöhle**	Hainholz, S-Harz, Niedersachsen; shallow phreatic solution cave (Stolberg, 1936; Kempe et al., 1972)	450 m
14. Großes Trogstein System***	Tettenborn, S-Harz, Niedersachsen; system of low, meandering vadose stream passages (Stolberg, 1928, 1932; Biese, 1931; Reinboth, 1963, 1969)	435 m
15. Schusterhöhle**	Tilleda, Kyffhäuser, Sachsen-Anhalt; shallow phreatic solution cave	434 m
16. Schlotte am Eduardschacht****	Mansfeld, E-Harz, Sachsen-Anhalt; deep phreatic solution cave (Kupetz & Brust, 1991)	400 m
17. Elisabeth-schächter Schlotte**	Sangerhausen, S-Harz, Sachsen-Anhalt; large, deep phreatic solution cave (Stolberg, 1943; Völker & Völker, 1982)	357 m
18. Höhle im Grundgips der Kläranlage****	Bad Windsheim, Franken, Bavaria; shallow phreatic solution cave	250 m
19. Segen Gottes Schlotte**	Sangerhausen, S-Harz, Sachsen-Anhalt; deep phreatic solution cave (Stolberg, 1943; Völker & Völker, 1982)	240 m

Notes: * = show cave; ** = accessible only by permission making them essentially inaccessible; *** = major parts no longer accessible; **** = not accessible at all

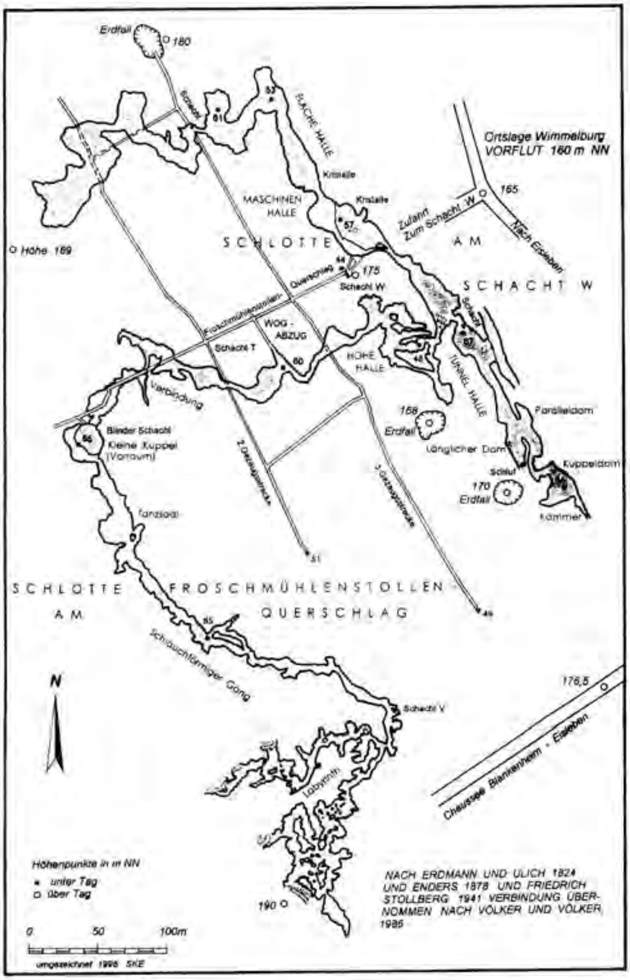

Fig. 4: Map of the Wimmelburger Schlotten, redrawn after various sources.

Many questions concerning the hydrodynamics of solution caves and the formation of facets and solution ceilings are still open to debate (see Reinboth, 1992). Nevertheless, we can now paint the following general picture of gypsum cave development: At places where water, not saturated with gypsum, can enter gypsum or anhydrite, it will quickly saturate with $CaSO_4$. This water can enter from two directions: from the sides or from below. Seepage water running into the cave through joints from above cannot aid in cave formation: it is already saturated with $CaSO_4$ after a few meters of percolation. This is shown by measurements made in the Jettenhöhle (Kempe et al., 1976; Kempe, 1982). Water entering sideways can be derived from sinking creeks (Marthahöhle, Hainholz, for example) or can be derived from groundwater percolating through a gravel-filled valley adjacent to the gypsum rock (examples: Heimkehle, Segeberger Höhle and Numburg-höhle). But water can also enter the gypsum rock from below because of the nature of the Zechstein salinar cycles: below each of the gypsum beds, a limestone or dolomite bed occurs. These beds, the

Zechsteinkalk for the Werra Series, the Stinkschiefer/Hauptdolomit for the Staßfurt Series and the Plattendolomit for the Leine Series, are subject to karstification themselves. They can conduct water far underneath the anhydrite bodies and cause attack of the anhydrite/gypsum bed from below. The water in the limestones is less dense and rises up into the gypsum because of buoyancy. Once saturated with gypsum, it becomes heavier and returns into the carbonate layer setting up a system of natural convection and continues its way downdip in the carbonate karst. This explains, where the water for the gigantic Schlotten-type caves came from and it was also shown to be the water-delivering mechanisms for the caves of the Hainholz (Kempe et al., 1976) (compare Fig. 2, B). There, rising groundwater can be seen in cave pools containing water of low gypsum saturation.

Once inside the gypsum rock, the water starts to attack the gypsum, forming dense solutions. At the ceiling of the developing caves a pattern of convecting "saltfingers" evolves, leaving small circular solution cups (Laugnäpfe), the size of finger tips (Kempe, 1969). At the cave walls a dense film of solution forms, sliding downward, smoothing the wall and forming the inclined smooth side walls so typical of solution caves (the facets) (Gripp, 1913; Kempe, 1975; Kempe et al., 1975). Thereby a convection is started involving the entire water body. Flat ceilings (solution ceilings) seem to develop if the solution is fast, i.e. if the water starts at a low saturation. The best example of a solution ceiling is found in the Marthahöhle where the level ceiling spans 20 m. If the water body operates near saturation, then the ceiling seems to attain more the shape of a cupola (like in the Schlotten-type caves) and the solutions cups are largely missing, indicative of large, and very slow convection cells (Kempe, 1996). At the same time the facets seem to recede in parallel to their starting position (Kempe, 1970). Solution experiments with salt models by Reinboth (1992) showed that the solution at the Laugdecke is about twice as fast as the solution at a vertical wall and about triple a fast as on a surface pointing upward. Solution from inclined surfaces seems to increase with the sinus of the inclination angle. It therefore remains a mystery, why the observed facets in nature seem to develop best at a slope of about 45°.

The general development of gypsum caves is given in Fig. 5. Caves formed by turbulent water flow are rather rare in Germany and the typical scallops caused by turbulent flow have been noticed in few caves as to date (Heimkehle, Kyffhäuser Caves for example). One of the few canyon-type gypsum caves is the very narrow Lichtenstein Cave (Kempe & Vladi, 1988). It must have formed very rapidly, possibly within a few years only, and then the water supply must have been cut off, otherwise the cave would not have been preserved. Another example of a gypsum cave formed by turbulent water flow is the Trogsteinsystem (Reinboth, 1963, 1968), where sinking creeks have formed meandering passages guided by a fault. The water reappears in the Fitzmühlenspring Cave on the other side of the ridge, a wide but extremely low cave passage following the joint pattern in large switchbacks.

In order to form solution caves (the most common type of gypsum cave in Germany) the water must percolate through the rock below a velocity causing turbulence. The solution cave development follows two branches (Fig. 5), one where the cave is developed at or near the water-table (shallow phreatic), the other where the cave development commences far below the water-table (deep phreatic).

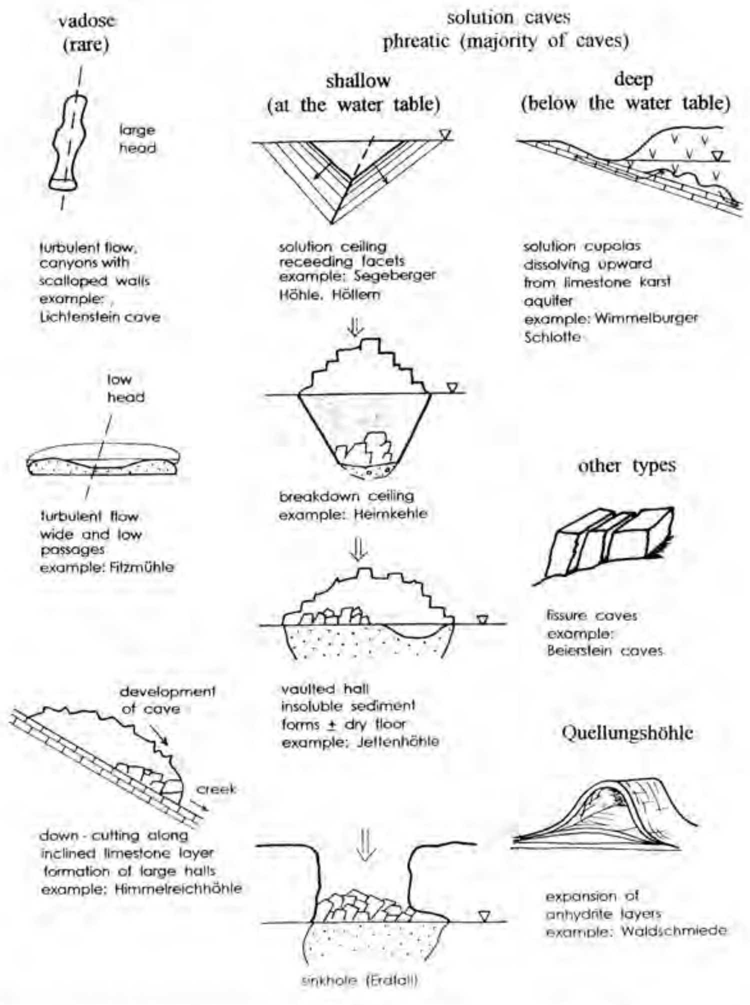

Fig. 5: Scheme of the general development of gypsum caves in Germany, explanation see text.

In the first line of development (center Fig. 5), the cave often starts as a maze of relatively narrow passages, as in the cases of the Segeberger Höhle, Marthahöhle and the Höllern, and is then more or less completely filled with water. It can grow above the watertable by breakdown once the solution cavity has undermined the walls far enough to cause instability. This breakdown can be dissolved completely or partially and insoluble sediments can fill the cave up to the watertable (Kempe, 1970). Typical examples for such caves are the Jettenhöhle, the Numburghöhle and the Heimkehle. Also the Barbarossa-höhle developed at a shallow phreatic level. It served as a path for the water collecting on the Kyffhäuser, sinking in the Zechsteinkalk and then dissolving its way through the steeply dipping A1 outward, at a level determined by the local watertable. Because the cave roofs are mostly rather thin, these caves very often end as a series of sinkholes (Erdfälle).

In the deep phreatic case (Fig. 5, right) cavities are formed far below the watertable (Kupetz & Brust, 1991). They tend to develop upward and not sideward. They follow the dip of the strata and can therefore be quite deep (vertical extent of the Wimmelburger Schlotten: 65 m). Normally they do not have any connection with the surface. However, breakdown can occur and can cause sinkholes at the surface (see map of the Wimmelburger Schlotten, Fig. 4). But this breakdown occurs underwater and the resulting vault will be smoothed by further solution causing the formation of large domes (Biese, 1931). One of the most famous of these domes is the Tanzsaal in the Wimmelburger Schlotte, where, in 1808, the famous geologist Johann Karl Freiesleben took his leave. Names inscribed during the party and the remains of a chandelier are still preserved (Völker & Völker, 1986). Stolberg (1943) counts 20 Schlotten and Völker (pers. com.) thinks that as many as 100 objects have been intersected by mining over the centuries. Two types can be discerned: The Wimmelburg Type (large, connected halls or low, wide, maze-like passages between 70 to 175 m below the surface) and the Ottoschächter Type (individual, pocket-like rooms up to 400 m below the surface) (Fulda, 1912; Kupetz & Brust, 1991). Due to the termination of the Kupferschiefer mining in the Mansfeld and Sangerhausen district, most of the Schlotten are now flooded and only a few remain, which still can be accessed providing proper permission by the mining administration.

Two more types of gypsum caves occur (Fig. 5, lower right): fissure caves and the so called "Quellungshöhlen". The fissure caves can be quite long. They occur at many places, specifically parallel to steep escarpments shedding off large blocks. Biese (1931) has reviewed this topic extensively. The "Quellungs" caves are a unique class of caves. They form due to the expansion (+26 vol. %) of the rock when anhydrite hydrates and recristallizes to form gypsum (Reimann, 1991). On the Sachsenstein, where most of these caves occur, anhydrite layers occur in parallel to the surface. When these layers increase in volume, they buckle upward and small blister-like cavities open up. Buckled layers of anhydrite changing into gypsum also hang from the anhydrite roofs of the Barbarossa- and Himmelreichhöhle.

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Chapter II.6

SOME EXAMPLES OF GYPSUM KARSTS AND THE MORE IMPORTANT GYPSUM CAVES IN SPAIN

Jose Maria Calaforra & Antonio Pulido-Bosch

Abstract

Spain possesses some of the most important examples of gypsum karst in Europe, in terms of the extent and variety of the gypsiferous outcrops. These are divided into gypsum belonging to the Triassic, Palaeogene and Neogene epochs, each of which displays different lithological and structural aspects. Some of Spain's most significant gypsum karsts, from the speleological standpoint, are described, and these share a common characteristic of all supporting the development of large caves. Reference is made to the geomorphology, hydrogeology and hydrochemistry of the gypsum karsts of Sorbas, Vallada and Gobantes-Meliones, which provide significant examples of intrastratal karst, speleogenesis by saline groundwater mixing and the influence of carbonate strata, respectively. Finally, brief geomorphological and speleogenetic descriptions of the more significant gypsum caves in Spain are given, together with a list of the longest and deepest gypsum caves in Spain.

1. Introduction

Spain contains some of the most extensive gypsum deposits in Europe. Some 30,000km2 of gypsum outcrop exists (Ayala et al, 1986), all of which is, in principle, susceptible to karstification. Not only is the area of such outcrops large, but there is also a great lithological and chronostratigraphical variety, with gypsum ranging from Triassic to Quaternary in age (Fig. 1). The most noteworthy outcrops, those most affected by karstification, are described briefly below.

Triassic gypsum. These deposits occur mainly to the Betic mountain range, though there are also significant outcrops in the Pyrenees and Iberian range. They are Keuper facies gypsum, with many clayey, sandy and carbonate intercalations. The group is intensely tectonized and is even affected by diapiric phenomena. Significant examples include the gypsum karsts at Baena (Córdoba; Calaforra and Pulido-Bosch, 1989), Fuente Camacho (Granada; Calaforra and Pulido-Bosch, 1989b), Estella-Allo (Navarra; Eraso, 1959), Gobantes-Meliones (Málaga; Calaforra, 1996a), Archidona (Málaga; Durán and Burillo, 1985), Antequera (Málaga; Molina, 1982), Caravaca (Murcia), Vallada (Valencia; Pulido-Bosch, 1978) and Villena (Alicante; Cuenca, 1970), among many others.

Palaeogene gypsum. These deposits are located to the north of the Ebro basin, close to the edge of the Pyrenees range. They present a great lithological variety, with massive gypsum, common levels of anhydrite and marly, carbonate and clay intercalations. Some significant outcrops

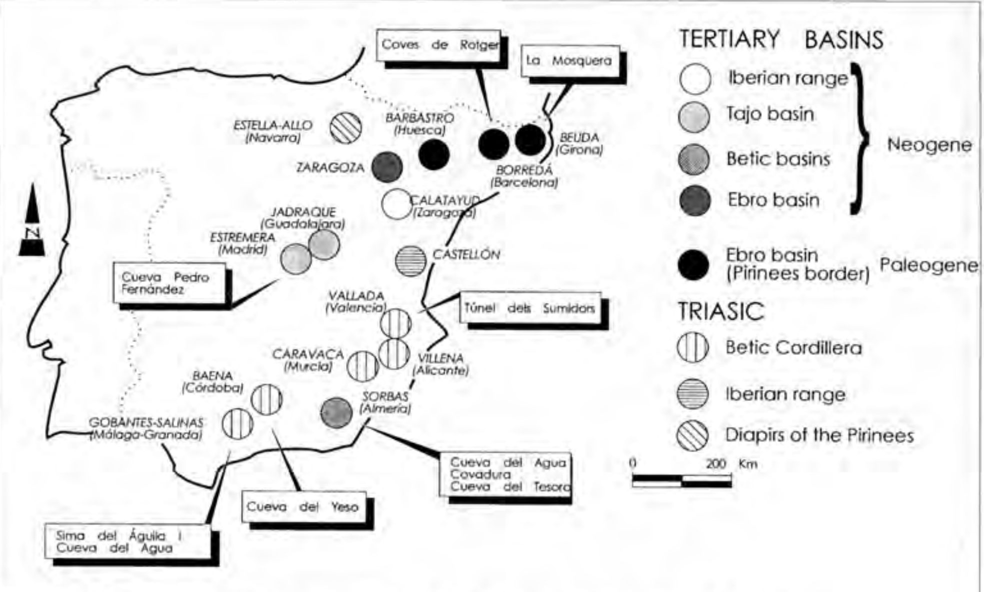

Fig. 1. Main karstic outcrops in gypsum, and the most important gypsum caves in Spain.

are those of Barbastro (Huesca; Gutiérrez et al, 1985), Beudá (Girona; Lloses and Robert, 1978) and Borredá (Barcelona; Noguera and Germain, 1985), and examples of gypsum karstification, such as the Banyoles lake (Girona; Sanz, 1985).

Neogene gypsum. These deposits occupy the greatest area, and represent an evaporitic sequence with abundant detrital intercalations and a great textural variety within the gypsum levels. They are limited to four principal locations: the Tajo basin, the Ebro basin and the Betic and Iberian Tertiary basins. The most noteworthy outcrops, with clear indications of karstification, are those of Estremera (Madrid; Eraso and Lario, 1988) and Jadraque (Guadalajara) in the Tajo basin (Durán et al, 1989), Zaragoza and its surroundings in the Ebro basin (Gutiérrez and Gutiérrez, 1995), Calatayud in the Iberian range (Gutiérrez, 1996) and the Sorbas basin in the Betic range (Pulido-Bosch and Calaforra, 1993).

2. Some Spanish gypsum karsts

The gypsum karsts that are described in greatest detail in this paper were chosen for their speleological interest. All the karsts hold caves that are significant, either because of their length, their depth or their particular mode of speleogenesis.

2.1 The gypsum karst of Sorbas

The gypsum karst of Sorbas, in the province of Almería (SE Spain), has an outcrop some 12km2 in extent. It lies within a topographic depression bounded to the north by the Filabres mountains and to the south by those of Alhamilla and Cabrera. The region has a semi-arid climate,

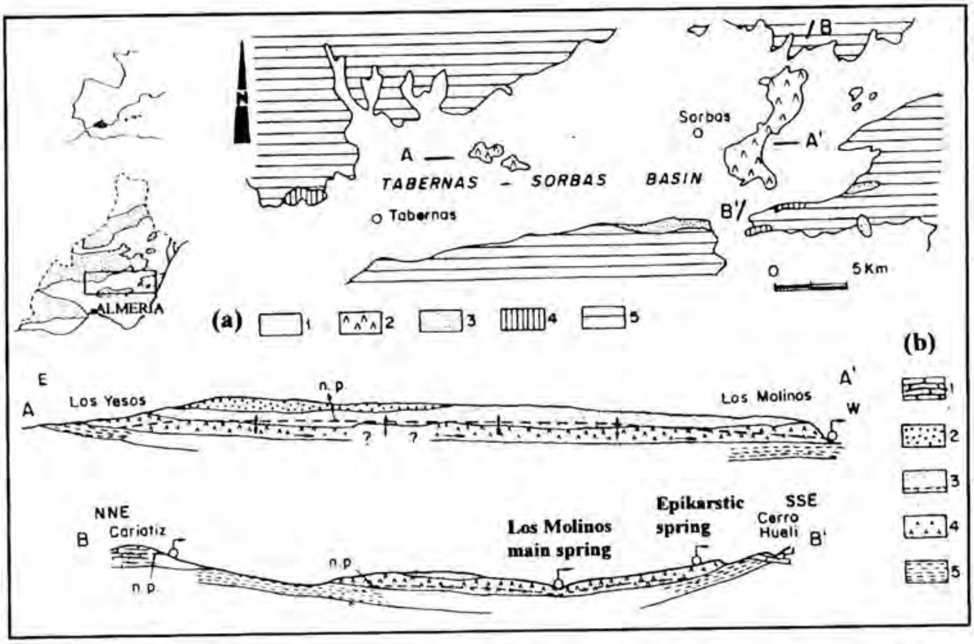

Fig. 2. Geological details of the gypsiferous outcrop of Tabernas-Sorbas (Almeria) (after Calaforra & Pulido-Bosch, 1997). Upper (a): 1- Neogene and Quaternary sediments (undifferentiated), 2- gypsum outcrops, 3-, 4- and 5- Betic units. Bottom (b): representative cross-sections, not to scale: 1- Reef limestone, 2- conglomerates (alluvial fans), 3- sandstones (coastal facies), 4- gypsum and interstratal marls, 5- silts (impervious base level), n.p.: piezometric level.

with a mean annual precipitation of less than 250mm. Mean annual temperatures are around 18∞C (Calaforra, 1985), but there are extreme contrasts between daily maximum and minimum temperatures during a large part of the year.

Geologically, the Sorbas karst, which lies within the Sorbas-Tabernas intra-montagne basin (Fig. 2), part of the Betic range, is developed within a cyclic sequence of intercalated gypsum and marly-pelitic materials; the whole sequence belongs to the Messinian Stage (Dronkert, 1977). The full succession has a thickness of about 120m, with gypsum intervals of up to 30m. Tectonically, the materials are only slightly folded, being almost horizontal, with a small degree of tilting caused by the presence of a syncline, with its limbs close to horizontal, that affects the gypsum. Fracturing and stratification, though hardly visible on the surface, commonly had a decisive role in guiding the linear development and the configuration of the levels in the caves (Calaforra et al, 1991).

The gypsum aquifer extends irregularly beneath the post-evaporitic materials, remaining semi-confined for much of its length (Pulido-Bosch and Calaforra, 1993). The main spring for the whole aquifer system (the spring at Los Molinos) has a mean flow of some 70 Ls^{-1} (Pulido-Bosch, 1982) and calcium-sulphate chemistry, with SIgyp values ranging between -0.1 and 0.0, and of -0.2 with respect to calcite (Calaforra and Pulido-Bosch, 1988). There is another group of springs, related directly to the drainage of specific caves, which present hydrochemical variations when compared to the principal drainage of the aquifer. These variations are manifested by lower contents of chloride, sodium and magnesium, enabling a clear hydrogeological distinction to be made between the two groups of springs (Pulido-Bosch and Calaforra, 1993).

Among the more significant geomorphological aspects is the great density of karst forms present (Pulido-Bosch and Calaforra, 1986). In an area of just 12km^2 almost 1,000 sinkholes have been identified (Calaforra and Pulido-Bosch, 1997) giving an idea of the intense surface erosion/dissolution that the area as undergone. Some of the karstic systems developed in this area have more than 20 entrances and galleries over 8km long (Cueva del Agua system; Ayuso et al, 1991) or depths exceeding 100m (Covadura system). Another noteworthy aspect is the presence of all types of karren and microkarren, comparable, morphologically, with similar developments in carbonate rocks (Calaforra, 1996b). The karstic typology most frequently found in the caves in this area corresponds to a scheme of erosional intrastratal karst (Calaforra, 1996a).

Gypsum karst evolution in the region began with the development of proto-conduits within the gypsum levels under semi-confined, or even confined, conditions within a multi-layer aquifer (Calaforra, 1996a). This stage must have progressed while continental post-evaporitic materials were being deposited, which itself implies an initial levelling of the karstic surface by the action of Plio-Quaternary erosional scouring. Subsequently, following the lowering of the piezometric level and partial erosion of the post-evaporitic sediments, the outcropping gypsum suffered a marked degree of surface erosion. This erosion also affected the marly-pelitic interbeds that were intersected in the already formed caves, developing cave passages with triangular erosional cross-sections.

Environmental problems concerning the karst of Sorbas have arisen, related particularly to the difficulty of its conservation (Villalobos and Calaforra, 1992). The special characteristics of this karst were the justification for it being declared an officially protected site. Nevertheless, uncontrolled mining and extraction of the gypsum continue to threaten the uniqueness of the area.

2.2 The gypsum karst of Gobantes-Meliones (Málaga)

The karstic outcrop of Gobantes-Meliones lies in the province of Málaga (southern Spain) in the neighbourhood of the Guadalhorce reservoir. The sector described is bounded by the Sub-Betic ranges of Humilladero (to the north) and Valle-Torcal (to the south) and the rocks belong to the geological group termed the "Trías de Antequera". Precipitation in this area is considerably more than in the Sorbas area, with values exceeding 700mm per year.

The karstified rocks overlie Triassic strata of Keuper facies. A high level of tectonic activity is indicated, as are the effects of diapiric behaviour (Fig. 3). The gypsum is commonly saccharoidal and microcrystalline; however, a whole range of materials are embedded in this, and they are, to a greater or lesser extent, allochthonous, giving the unit a unique breccia-like appearance. In fact, an olistostromic origin has been suggested for these materials, explaining the presence of rocks from other Subbetic units (Martín-Algarra, 1991). If this interpretation is accepted, the formation of this mega-breccia would have to be attributed to events during the Miocene epoch, as a product of the displacement of Triassic sediments during the movement of the Guadalquivir olistostrom. Morphologically the outcrop comprises two large sub-circular masses, each with a gypsife-

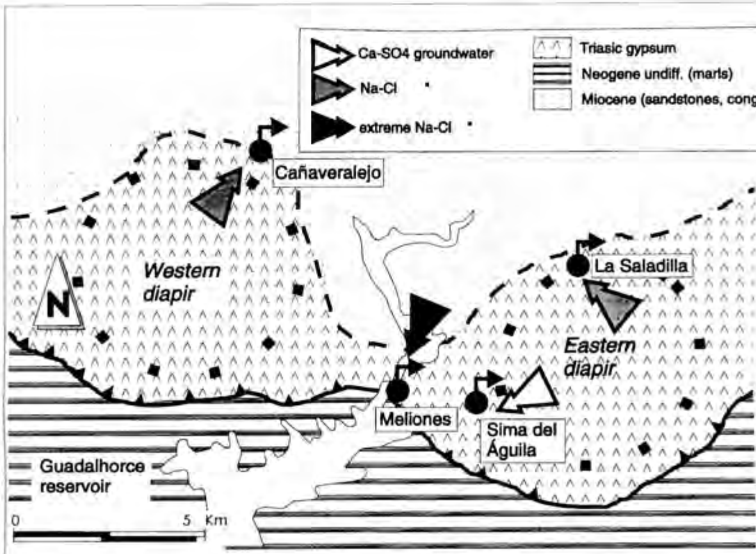

Fig. 3. Geological and hydrogeological setting of the gypsiferous outcrop of Gobantes-Meliones (Málaga).

rous centre and sandstones, ophites and dolomites in the outer parts. This morphology and facies distribution might reflect the halo-kinetic behavior of these materials, a supposition that is supported by the existence of hyper-soluble salts at depth.

From the hydrogeological viewpoint, it is important to distinguish between the springs related to a highly saline deep flow (the Meliones and Cañaveralejo springs) and those springs with calcium sulphate chemistry, which drain only the Triassic gypsiferous beds (Carrasco and Benavente, 1986; Calaforra, 1996a). This duality is also found in other, nearby, karstified gypsum outcrops, such as that of Salinas-Fuente Camacho (Granada; Calaforra and Pulido-Bosch, 1993), which is also developed within a part of the "Trías de Antequera" group. The spring at Meliones, with a mean flow of some 10 Ls^{-1}, has a conductivity of over 200,000 mS cm^{-1} (Calaforra, op. cit.). This reflects a high groundwater salinity, around five times greater than the salinity of the Mediterranean, and gives some indication of the huge quantity of dissolved salts in its waters.

The caves that have been explored in this region are generally small, with notable exceptions, such as Sima del Aguila, with a depth of over 100m or Cueva del Negro, with a length of over 1km (Ramírez, 1995). These are frequently mixed caves, which have developed jointly within carbonate beds (boulders within the olistostromic breccia) and gypsiferousstrata.

Although the evolution of the gypsum karst of Gobantes-Meliones is currently governed by the apparently simple effect of dissolution upon the surface outcrop, various other factors may impinge upon this evolution and intensify the karstification process. One of these could be related to the halo-kinetic uprising of materials, which has enabled many of the caves to evolve in a vertical form, or to remain active above the base level at present occupied by the Guadalhorce river (Durán, 1984). A second potential process involves the phenomenon of hyper-karstification, resulting from the effect of salt water mixtures (Calaforra, 1996a), markedly intensifying gypsum dissolution, at least at depth. Finally, it has been noted that the processes of dolomitization and de-

Plate 2. The Complejo GEP (gypsum karst of Sorbas, Spain). An intrastratal cave.

3. The most significant gypsum caves in Spain

This section describes the most notable or significant gypsum caves in Spain. It includes those of noteworthy length or depth, together with other examples that are significant because of the geological or hydrogeological surroundings in which they have developed.

Cueva del Agua, 8350m long (karst of Sorbas, Almería)

This cave contains the most extensive gallery systems yet discovered in Spain (Baquero and Calaforra, 1994; Plate 1). It is located in the closed depression of the same name, in the northern part of the Sorbas gypsum outcrop. The basin forming its catchment is 1km^2 in area and includes almost 100 sinkholes, with diameters not exceeding 40m (Calaforra et al, 1991). It is currently being explored by the Almería Speleological Club (E.C.A.), and to date 24 different entrances to the system have been identified. A small watercourse runs through the cave, with a mean flow of less than 1 Ls^{-1} (Calaforra et al, 1993), though in periods of heavy rainfall this may reach 1 m^{3}s^{-1} (Calaforra, 1996a). Two levels have been distinguished within the cave, separated by one of the marly intercalations that are characteristic of the gypsum sequence. The upper level features inter-stratification galleries and the lower one, frequently flooded, presents ancient and contemporary phreatic morphologies.

Covadura, 4245m long (karst of Sorbas, Almería)

This is the second longest and one of the deepest gypsum caves in Spain. It lies in the northern sector of the Sorbas gypsiferous outcrop, at a point where the evaporitic sequence is almost complete, and has not suffered any marked degree of erosion. The cave has developed across six different levels, each of which is located along the stratification planes between gypsiferous beds and marly intervals. The whole set of levels spans a vertical range of 126m, which is the approximate thickness of the gypsiferous succession. The cave originated under flooded conditions within a multi-layer aquifer, which subsequently evolved to become an erosive intrastratal karst (Plate 2; Calaforra, 1995).

Cueva de Pedro Fernández, 3204m long (karst of the Tajo river basin, Madrid)

This is one of Spain's most important archeological caves, and hence access to the cave is currently restricted. It lies close to the town of Estremera, in the province of Madrid, and has developed in the Neogene evaporitic sediments of the Tajo basin. The main characteristic of the cave, differentiating it from other caves that have formed in Spain, is that it is a maze cave (Almendros and Antón, 1983), with a network of intersecting galleries that follow various lines of structural weakness (Eraso and Lario, 1988). The cave's origin reflects confined aquifer conditions, related to changes in water levels within the tributaries of the river Tajo (Calaforra, 1996a).

Plate 3. Tunel dels Sumidors (gypsum karst of Vallada), the deepest known gypsum cave in the world, showing an interbed of dolomite breccia in the cave.

Coves de Rotgers, 920m long (karst of Borredá, Barcelona)

This cave is special due to the characteristics of the materials in which it has is developed. These are marls and limestone with local interbeds of gypsum and anhydrite. The cave has very narrow passages and galleries that reach a depth of 79m in one of the gypsum-anhydrite interbeds. The gypsum material displays the effects of changes produced by anhydrite hydration, a process that drove one of the first phases in the development of the cave.

Longest gypsum caves of the Spain

Cave	Town	Province	Length
1. Cueva de Agua system	Sorbas	Almería	8350m
2. Covadura	Sorbas	Almería	4245m
3. Pedro Fernández cave	Estremera	Madrid	3204m
4. Cueva del Tesoro	Sorbas	Almería	1890m
5. Cueva del yeso	Baena	Córdoba	1843m
6. Sistema del Peral	Sorbas	Almería	1800m
7. Cueva de los Apas	Sorbas	Almería	1500m
8. Cueva del Negro	Antequera	Málaga	1236m
9. Túnel dels Sumidors	Vallada	Valencia	1232m
10. Cueva de los Ruidos	Sorbas	Almería	1117m

The deepest gypsum caves of the Spain

Cave	Town	Province	Depth
1. Túnel dels Sumidors	Vallada	Valencia	210m
2. Sima del Corral	Sorbas	Almería	130m
3. Covadura	Sorbas	Almería	126m
4. Sima del Campamento	Sorbas	Almería	122m
5. Sima del Aguila	Antequera	Málaga	112m
6. Sima del Plástico	Sorbas	Almería	96m
7. Sima del Yoyo	Sorbas	Almería	95m
8. Cueva del Lapo	Sorbas	Almería	94m
9. Cueva de los Ruidos	Sorbas	Almería	80m
10. Coves de Rotgers	Borredá	Barcelona	79m

Tunel dels Sumidors, 210m deep (karst of Vallada, Valencia)

This is the deepest known gypsum cave in the world (Calaforra et al, 1986). The principal gallery (Plate 3) has many passages that are almost horizontal. It is interrupted by abrupt projections, and pits up to 20m deep, coinciding with vertical fractures and dolomitic interbeds. These are especially common in the final part of the gallery. A watercourse with a mean flow of about 5 Ls^{-1} runs through the whole length of the cave, and is derived from the infiltration of small springs at the watershed. The cave ends at a siphon that is connected hydrologically to the saline spring of Saraella. Complete exploration of the siphon has not yet been possible.

Sima del Aguila, 112m deep (karst of Gobantes-Meliones, Málaga)

This is the most significant cave within the Gobantes karst and its ramifications are essentially vertical. Its initial part is developed along the contact between the gypsum and the Triassic limestone-dolomites, such that the pits follow the contact plane. At intermediate depth the cave collects infiltration waters from a small surface stream flowing over the gypsum. In its final part, the fissure reaches a massive bed of breccia with a microcrystalline gypsiferous matrix, forming a large chamber 30-40m high with an area exceeding $200m^2$, formed in response to the sudden lithological change and associated gravi-clastic processes.

4. Large gypsum caves in Spain

Finally, a revised catalogue is provided of the largest gypsum caves in Spain, classified both by length and depth. Note that only two caves are not in the Betic mountain range and more than 60% of the total are located in the gypsum karst of Sorbas (Almeria).

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Chapter II.7

THE GYPSUM KARST of ITALY

Paolo Forti & Ugo Sauro

Introduction

Gypsum karst has been studied in Italy since the last decades of the 19th Century. In 1917 the geographer Olinto Marinelli published "Fenomeni carsici delle regioni gessose d'Italia", a fundamental synthesis of the early research. He distinguished 56 different morpho-karstic gypsum units and/or areas, which are all different in size and character (Fig.1), and described them, paying special attention to their surface morphology and hydrology. Marinelli listed all the main gypsum units and only a few secondary outcrops were overlooked.

After Marinelli's synthesis, except for some discussion of archaeological caves, only a few papers about gypsum karst and environment were published until the nineteen-fifties. In the nineteen-sixties and seventies much exploratory work and documentation was carried out in the Emilia Romagna area, principally devoted to the gypsum caves, and undertaken by the local speleological clubs and university researchers (Bertolani & Rossi, 1972a, 1972b; Gruppo Speleologico Emiliano et al, 1966, 1972).

An important milestone in the history of knowledge about the gypsum karst of Italy was the International Symposium on Evaporite Karst held in Bologna and Palermo during 1985 (P. Forti & P. Grimandi [Eds], 1986; P. Forti, V. Agnesi, T. Macaluso, M. Panzica La Manna [Eds], 1987). This symposium enhanced gypsum karst research in Italy and encouraged exploratory work by the speleological clubs. Two main inter-disciplinary research projects on gypsum karst morpho-units have subsequently been undertaken (P. Forti, V. Agnesi, T. Macaluso [Eds], 1989; G. Ferrini [Ed], 1997).

The chapters that describe gypsum karst surface landforms in this publication contain many references to examples of gypsum karst in Italy, and these supplement the descriptions provided below.

1. The geographical and geological framework of gypsum karst in Italy

The largest gypsum formation outcrops are those in Sicily, with a total outcrop area of more than 1,000km^2 (Forti et al, 1987). Emilia Romagna follows, with outcrops totalling little more than 100km^2 (Bassi et al, 1989; Casali et al, 1983; Costa et al, 1994). The numbers of surveyed caves in these regions are about 200 and more than 500 respectively. In the Alps the best known area of gypsum is that of Colle del Piccolo Moncenisio, with an extent of several km^2. Otherwise, the more extensive gypsum "outcrops" are within submarine "closed basins" on the floor of the Mediterranean, and details of their geomorphology are only poorly known.

From the geographical viewpoint Italy's gypsum karst areas have developed across a wide range of latitudes, altitudes and morpho-climatic zones. They extend between latitudes 37° and 47°N and altitudes from sea level to more than 2,700m a.s.l. in the Alps. Gypsum karst areas occur

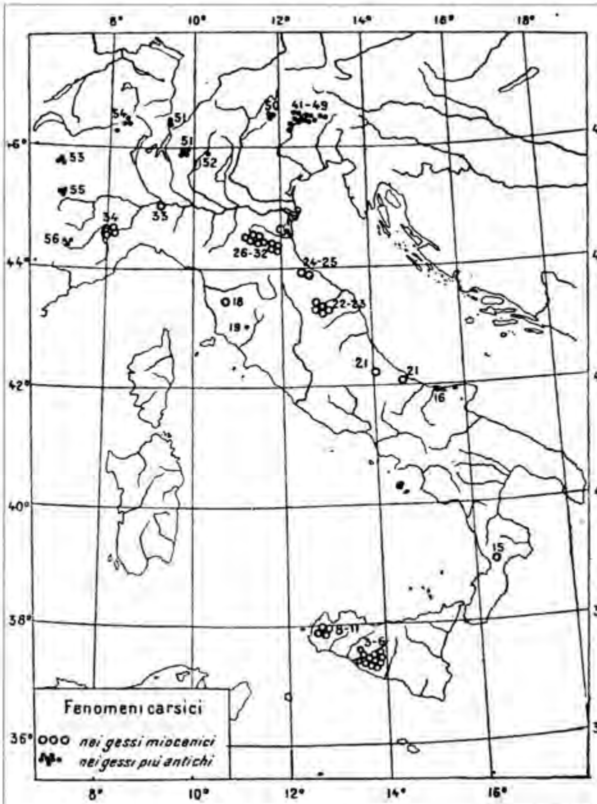

Fig. 1 - The morpho-karstic gypsum units and/or areas of Italy according to the figure published by O. Marinelli in 1917. Marinelli identified all the main gypsum units.

in fold belts associated with the Alpine Orogeny and also in marginal areas (Sardinia). The climates vary between humid middle latitude mountain types and semi-arid Mediterranean types.

From the stratigraphical viewpoint three main groups, or complexes, of gypsiferous rock formations can be distinguished: a Palaeozoic complex, an early Mesozoic complex, and a late Neogene complex (Desio, 1973).

The Palaeozoic evaporites are a typical transgressive sequence, known as the Formazione a Bellerophon, that was deposited in a semi-arid coastal lagoonal environment during the Late Permian. It consists of a series of cycles, each cycle starting with grey dolomite and clay, and ending with beds of gypsum. The formation is up to 400m thick, and it crops out on valley sides in the Southern Alps, near Friuli, Veneto and Trentino.

The Mesozoic complex, comprising a sequence of Late Triassic age, is recognized in the western Alps, around the border between Italy and France, in the Northern and Adriatic Apennines, and in Sardinia.

The Neogene complex is more significant. Of late Miocene (Messinian) age, it is called the Formazione Gessoso Solfifera, and is recognizable at surface outcrop and in buried successions throughout most of the peninsular, from the Northern Apennines to Sicily. This complex is the product of a highly significant palaeogeographical event that occurred between 6.5 and 5 million years ago, when the Mediterranean basin became closed, losing its connection with the Atlantic Ocean. The isolated Mediterranean sea shrank, leaving several salt lakes nested inside crypto-depressions nearly two thousand meters below the original sea level. In these over-saturated lakes great volumes of salts were precipitated, contributing to thick evaporite formations made up mainly of gypsum and rock salt. During the late Miocene, Pliocene and Quaternary these formations were partly affected by the Alpine Orogeny, and have become part of the tectonic fabric of the Italian peninsula.

In the Northern Apennines the Formazione Gessoso Solfifera outcrop is effectively homoclinal, dipping towards the Po Plain. Starting from the base, the formation includes bituminous clayey marls, evaporitic limestone, and thick layers of gypsum with thin marly intercalations, for a total thickness of about 150m. The underlying rock unit is the Formazione Marnoso-arenacea romagnola, a flysch-like complex of Tortonian to Langhian age, with a total thickness that ranges between 4,000 and 5,000m. The overlying Formazione a Colombacci, comprises clayey and silty marls with intercalations of evaporitic limestone lenses. This formation locally shows a sharp angular unconformity at its base, the expression of a deformational episode and erosional phase that occurred at the end of the Messinian. A latest Messinian vertebrate fauna has been discovered within palaeokarst features just below this discontinuity (Costa et al, 1986). Overlying these formations are transgressive clayey and sandy beds of Pliocene age.

In Sicily the Formazione gessoso solfifera comprises two main lithostratigraphical units with a maximum thickness of 1500m, underlain by a siliciclastic unit (Formazione di Terravecchia) and covered by clayey marls (Trubi) and clay. From the bottom to the top the lower evaporitic unit consists of: a) diatomite and diatomaceous marls (tripoli), b) evaporitic limestones, c) gypsum with intercalations of gypsiferous marl, d) salts (mostly chlorides). The upper evaporitic unit consists of: a) cycles of gypsum and gypsiferous limestones with sandy and clayey layers, b) bioclastic limestones changing laterally and upwards into gypsum, c) clayey sands (arenazzolo).

In western Sicily there are commonly sulphur mineral ores within and at the base of the microcrystalline gypsum beds.

In some parts of Sicily and Calabria the gypsiferous formation is cut by an erosion surface and is buried with angular unconformity by clastic sediments, such as calcarenites or transgressive conglomerates, and unconsolidated coastal and fluvial sediments.

2. Main types of morpho-structures

From the morpho-structural standpoint the main gypsum morpho-units comprise tabular blocks, of plateau and mesa type, homoclinal ridges of cuesta type, dome-like hills, outliers sitting on older clastic formations, bands along some major slopes contained within multiple folds, and tectonic slices inside complex structures.

The most distinctive, and the largest, morpho-structure within the Italian peninsula is a homoclinal ridge, locally displaying bevelled cuesta topography and cut by many water gaps. This structure, called the Vena del gesso, extends across the Northern Apennines between Bologna and the Adriatic Sea,and its main sector is 25km long, but very narrow.

In Sicily there are many large- and medium-sized morpho-structures, some displaying the characteristics of tectonic wedge plateaux (for instance the Santa Ninfa Plateau), or of tabular plateaux (such as Serra Ciminna), or homoclinal ridges (like Serra Balate).

3. The surface forms

In some areas the gypsum outcrops are almost completely covered by soil and vegetation, though elsewhere rocky surfaces dominate. Thus, gypsum pavements, with typical weathering aspects and karren forms, are exposed at some localities.

There are some typical blind valleys in the gypsum karst of the Northern Apennines and in Sicily. In the Northern Apennines the Rio Stella - Rio Basino creek valley, more than 1.5km long, is developed in clayey marls and ends against the high rocky bluff of Vena del gesso, in macrocrystalline gypsum, where a ponor swallows the waters (there is also a 1.5km-long cave system crossing the ridge). In Sicily the best known blind valleys are developed mostly within gypsum or in clayey marls that overlie gypsum. Examples are the blind valleys of the Biviere creek in the gypsum plateau of Santa Ninfa, about 2.5km long, and Lo Sfondato north of Porto Empedocle. All the related ponors feed active cave systems.

A wide variety of sizes and aspects of dolines are present. There are populations of very small dolines (1.5-6m in diameter and 0.2-1.5m deep), as in the Dolomites (Bini, 1983) and the western Alps (Capello, 1955). There are also groups of very large dolines, with diameters of several hundred metres, as in the Vena del gesso area. Many intermediate forms between blind valleys and dolines also exist, especially in the gypsum karst of Sicily. From the morphological point of view, there are funnel-shaped and pit-like dolines, bowl- and plate-shaped dolines, nearly symmetrical plateau dolines, and asymmetrical slope dolines.

The large variety of dolines recognized in some gypsum areas is underlined by the classification suggested by Capello (1955), for the high mountain gypsum karst of Moncenisio in the western Alps. Capello distinguished the following types: a) symmetrical funnel-shaped dolines, b) symmetrical flat-bottomed dolines (or saucer-shaped dolines), c) asymmetrical dolines, d) bowl-shaped dolines, e) pit dolines, f) pits, g) corridors derived from the fusion of several dolines. In type e) both typical cylindrical dolines and half-funnel dolines swallowing small rivulets are included. The sizes of these dolines range from a few to more than 100m in diameter and from a few to more than 20m in depth (Fig. 2).

There are also polje-like landforms that, from the hydrological point of view, are normally open but represent "ponors". They are relatively common in Sicily (such as il Pantano, to the west of Siculiana Mare). In the Alps a glaciokarstic polje, the polje of La Valoire, was described by Nicod (1976).

4. Surface landforms in rocks overlying gypsum

Some closed depressions develop by subsidence and collapse within non-karstifiable rocks that overlie gypsum.

In Italy doline-like forms and large, but shallow, closed basins, are both present. In Sicily there

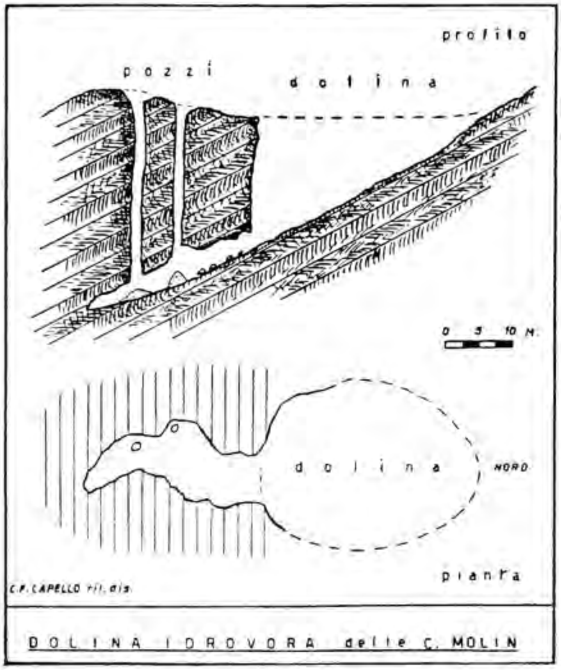

Fig. 2 - Cross-section of a complex landform in the gypsum karst of the alpine area of Moncenisio (After Capello, 1955).

are many large depressions that are normally occupied by lakes, with surface areas ranging from a few hundred m^2 to about $2km^2$. The Pergusa lake, near Enna (Sicily), has a surface area of $1.83km^2$ and a maximum depth of only 4.6m. In the Alps there are both subsidence dolines and collapse dolines. In the Moncenisio area two new collapse dolines opened during the summer of 1965 (Nicod, 1976), and in the Agordo Valley (in the Dolomites) many new subsidence and collapse dolines have formed during the last few decades. In the braided bed of the Tagliamento River, in the Southern Alps, many collapse phenomena have occurred during this century (about 10 during the decade 1955-1964 according to Gortani, 1965). Other collapse phenomena are described in the urban area of Gissi in Southern Abruzzo (Burri, 1986).

5. Hydrological aspects and caves

In the gypsum karst of Italy the only areas carefully surveyed by speleologists are the Vena del gesso in the Northern Apennines, the Verzino plateau area in Calabria and the Santa Ninfa plateau in Sicily. Most areas still await investigation and it is inevitable that many more caves will be discovered in the future.

Nevertheless, Italy hosts some of the world's deepest and more complex gypsum caves. This reflects both Italy's Mediterranean climate, which supplies large volumes of water seasonally to the deep circulation systems, and the presence of thick and highly tectonized gypsum sequences. These conditions support development of extensive and deep caves during relatively short timescales.

From the hydrogeological viewpoint hardly any of Italy's gypsum caves appear to owe their genesis to lateral or basal injection. Nearly all of them seem to be normal seepage caves, developed entirely within the percolation zone. In fact, they are generally the expression of hydrogeological systems with a very low level of hierarchy. They show a very simple hydrological structure that may be viewed schematically as comprising a main, sub-horizontal, drainage tube following the piezometric surface, with only a few, or without any, small secondary tributaries. Connections with higher inlet points are always represented by vertical pits. No truly phreatic structure can exist in this type of cave. In those caves that show evidence of several superimposed levels the structure is related to sequential steps in the lowering of local base level.

In the Vena del gesso nearly 500 caves have been explored and mapped, and nearly 100 important hydrogeological systems have been identified (Badini, 1967; Bertolani et al, 1980). In Sicily there are nearly 200 known caves, and only a few in Calabria. From the point of view of their interactions with surface hydrology, it is possible to distinguish the following types of cave:

a) hydrogeological through caves, that lead from a sink point at the closure of a blind valley or in the floor of a large doline and terminate as spring caves; these caves are normally multi-level systems;

b) sink caves, that are similar to the previous type but do not present explored connections through to spring systems;

c) spring caves, that are also similar to type a) but do not present explored connections back to sink systems;

d) active caves with streams flowing underground but having no explored connection to either sink or spring systems;

e) relict inactive caves, currently dry and lacking connections to an active hydrological network;

f) tunnels formed as "hypogean meanders", developed laterally as loops from valley floors and consisting of sink caves, twisting active underground passages and cave-springs (Chiesi, 1989).

Some of the more important surveyed caves are listed in table 1.

There are also many small tectonic caves and some vertical systems developed in gypsum. The deepest shaft so far described is the "Pozzo A", near the mountain refuge of Moncenisio, which is more than 200m deep (Dainelli, 1908; Capello, 1955). There is no up-to-date information about the state of this shaft, or that of the Grotta Gianset, over 100m deep, which is not far from the first. Their current condition may depend upon a variety of unique factors that affect each individual high mountain shaft, as in general they will all undergo a very fast evolution (several metres, if not tens of metres, per year), precluding the possibility of their existence extending over long periods.

From the point of view of the geomorphology of the subterranean cavities the following types can be distinguished:

m) tunnels resulting from "horizontal erosion", and/or from the fusion of several sub-horizontal tubes;

n) pseudo-galleries, resulting from the fusion of several cavities, most commonly formed by vertical percolation along fissures;

o) cylindrical and "ogival" (arch-shaped) pits and cavities;

p) waterfall pits, locally with potholes, Table

SOME OF THE MAIN GYPSUM CAVE SYSTEMS OF ITALY

Name	region	rock age	type	number of levels	length(m)	depth(m)
Spipola-Acquafredda	ER	M	a	4	10.400	110
Ingh. SW di Ca' Siepe	ER	M	b	3	2500	205
Re Tiberio"	ER	M	c	3	2110	75
Tre Anelli"	ER	M	b	3	1074	144
Abisso 50"	ER	M	b	2	1200	149
Rio Stella-Rio Basino•	ER	M	a	+	1500	100
F10+•	ER	M	b		1450	210
Grave Grubbo *	CA	M	d		1470	48
Grotta dello Stige*	CA	M	c		575	21
S. Ninfa	SI	M	c	+	1350	25
M. Conca °	SI	M	b		500	90
M. Conca °	SI	M	c		250	
Tanone della Gaggiolina	ER	T	f		420	40

Key: Region - ER = Emilia e Romagna, CA = Calabria, SI = Sicily
Gypsum age - M = Messinian, T = Triassic
Type - see the types described above
the caves indicated with the same symbols as: ", •, *, °, are part of the same active system.

q) collapse chambers;

r) cavities formed due to slope tectonics.

A very common feature is the "pseudo-phreatic tube", which is similar in appearance to a normal phreatic conduit but develops starting from tunnels that are almost completely filled by sediments, and so has its roof and walls in gypsum and its floor in sediment. If the sediments are eroded typical galleries with ceiling half tubes result.

Within the main drainage tubes of some active caves in gypsum the presence of suspended material in the water has been demonstrated as being by far the main influence upon the enlargement of some active cave passages. On average mechanical erosion represents over 60% of the overall mass wasting of the cave walls. Condensation dissolution is the second most important effect (about 30%), and normal dissolution is by far the least active process in this situation. In the Grave Grubbo Cave, over 1cm of riverbed lowering was measured by means of M.E.M during a single 28-hour flood.

Chemical deposits are scarce in Italian gypsum caves, but they are generally more common than in other climatic areas of the world. Most recorded examples are of calcite speleothems, but gypsum speleothems are found in the south of Italy. Only a few gypsum karst areas in Italy have been studied with specific regard to their chemical deposits, but they are the only ones in the world where such detailed mineralogical work has been carried out. For this reason, over 90% of all the world's secondary cave minerals described from gypsum caves to date were detected in Italy.

From the hydrodynamic viewpoint, it is clear that during flood conditions solvent water in the active karst systems flows rapidly (20-40cm/sec) and is heavily loaded with suspended material. In the underground galleries erosionally and depositionally significant episodes both occur frequently. Generally the water can keep the main passages open, even where there is a significant supply of clastic material.

6. Types of karst

A wide variety of karst types can be distinguished according to their geological and geomorphological evolution (see chapter 1.4). In general, the stratigraphical settings are such that the main evaporitic complexes were originally confined by adjacent impervious formations, that preserved them from contact with underground water. However, episodes of deformation and the morpho-dynamic development have allowed the water to penetrate, allowing karstification to begin in deep-seatedsituations.

Undoubtedly the most important gypsum karst setting in Italy is deep-seated karst, both in submarine and terrestrial environments. The many closed subsidence depressions in Sicily, some of which are occupied by lakes, are probably related to lateral water injection into deep-seated gypsum karst from adjacent aquifers.

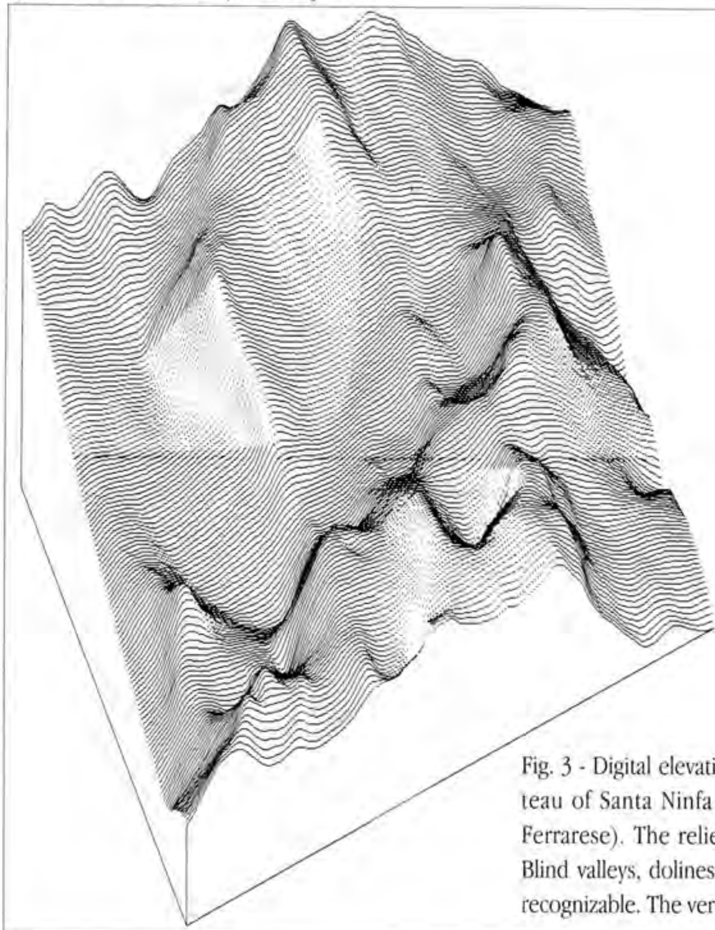

Fig. 3 - Digital elevation model of part of the plateau of Santa Ninfa in Sicily (elaborated by F. Ferrarese). The relief is complex and irregular. Blind valleys, dolines and intermediate forms are recognizable. The vertical scale is exaggerated.

In some karst morpho-units, such as the Altopiano of Santa Ninfa in Sicily, transitional situations between subjacent karst, entrenched karst and denuded karst are found. From the morphological standpoint this is expressed by the co-existence of active valleys, dry valleys, blind valleys, doline chains and clusters of dolines that tend towards a honeycomb pattern. Each of these types can be correlated with a definite stage of cover rock erosion (Fig. 3).

Interesting examples of buried karst are present in some parts of Sicily (such as Serra Ciminna, Siculiana Mare), where permeable covers preserved above erosion surfaces cut in gypsum have favoured the development of an interface karst. Where later erosion exhumed this karst, unusual landscapes have developed, with deep clefts and trenches separating upstanding rocky features of stone forest and karren table type (Ruggeri & Torre, 1987).

Buried and exhumed karst have both been described in the Vena del gesso. In particular, an erosion surface of late Messinian age has been buried and fossilized by the Formazione a Colombacci. A fossil terrestrial vertebrate fauna of late Messinian age has been found in the neptunian infillings of some palaeo-karst cavities (Costa et al, 1986).

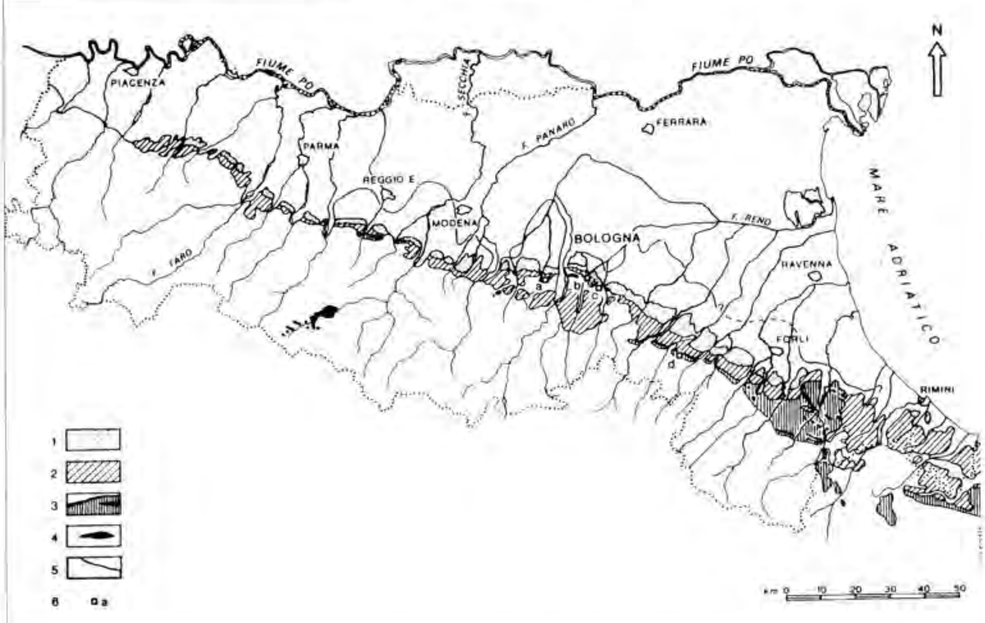

Fig. 4 - Geomorphological and hydrogeological sketch of a sector of the Vena del gesso near Bologna (from Forti, Francavilla et al. 1985): 1 = alluvial plain deposits; 2 = valley bottom alluvial deposits; 3 = Messinian marls; 4 = gypsum outcrops; 5 = undifferentiated clay; 6 = blind valleys (A: Valley of Rio Acqua Fredda; B: Buca di Ronzano); 7 = main dolines; 8 = nested dolines; 9 = main scarps; 10 = main underground watersheds; 11 = secondary underground watersheds; 12 = direction of the underground flow; 13 = karstic resurgences; 14 = permeable "dike"; 15 = semi-permeable "dike"; 16 = hydrogeological barrier.

Considering this unconformity and its palaeokarst, the following hypothetical evolutionary model may be deduced for the sections with well developed karst landforms:

a) tectonic uplift and tilting of the surface, with development of a system of consequent valleys running down the dip and crossing the different rock units;

b) exhumation of the erosional palaeo-surface;

c) selective erosion, with favoured development of a bevelled cuesta type gypsum ridge, erosional valleys cutting water gaps in the ridge, and small dolines evolving on the ridge by re-activation of old karst features;

d) closure of some blind valleys developed inside the gypsum ridge; a retreat of sink points that develop sequentially at the upstream limit of the gypsum band, at the lithological contact between gypsum and clay formations;

e) the old depressions with sink points on the ridge evolve as large dolines.

Examination of the areas confirms that, as predicted, there are blind valleys that have cut through large crossing cave systems and big dolines with caves that also represent parts of old crossing systems (Fig. 4).

7. Human impact and conservation

The human impact upon the gypsum karst of Italy has been generally very strong since prehistoric times. Deforestation of the primary Mediterranean forest, the use of the land for agriculture and sheep or goat grazing has encouraged soil erosion and denudation of the rock on many slopes (Burri, 1989). The environmental fragility is greater in southern Italy, where, during the summer, there is a higher soil water deficit and vegetation is more susceptible to fires. Large areas of bare gypsum outcrop displaying exceptional weathering forms, especially karren, are now found in Sicily.

Quarrying is a more recent form of human impact. In the Vena del Gesso many large quarries have been opened since Roman times. Mediaeval towers in the town of Bologna were built with blocks of macro-crystalline gypsum. During this century larger quarries have been opened, leading to the destruction of some caves (Badini, 1967), and a famous cave system with many archaeological remains was damaged by quarrying (Varani, 1974).

In the gypsum karst of Moncenisio the construction of a dam caused a considerably enlargement of a natural lake. This resulted in activation of underground karstification, that was manifested at the surface as collapse phenomena.

Recent development activities in ski resort areas, particularly work on the construction of ski runs, has accelerated the denudation of some gypsum outcrops. At Cervinia, in the Aosta Valley, very rapid evolution of grikes and shafts has been observed, and on one occasion a sno-cat fell into a shaft.

In some valleys of the Southern Alps (for instance the Agordo valley) the increased urbanisation of certain areas, caused by the building of second homes, has triggered several instability and collapse phenomena due to the influence of deep-seated or buried gypsum karst.

In recent times natural reserves and parks devoted to gypsum karst have been established.

The best known are the Parco dei gessi of Bologna, and the Riserva Naturale di Santa Ninfa in Sicily.

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Chapter II.8

GYPSUM KARST OF THE EASTERN-EUROPEAN PLAIN

Vjacheslav Andrejchuk & Alexander Klimchouk

1. General characteristics

The Eastern-European Plain (abbreviated EEP; also known as the Russian Plain) is one of the largest plains in the world. It extends north to south from the Arctic Ocean coast to the foothills of Caucasus Mountains for almost 3,000km, west to east from the Carpathians to Ural Mountains for more than 2,000km.

The geological foundation of the plain is the Precambrian East-European platform, complicated by numerous anticlines, synclines, fault steps and depressions in the crystalline basement. The thickness of sedimentary cover varies from zero, where the crystalline rocks crops out at the surface (the Ukrainian and Baltic shields), to 5-6km or more in grabens, basins and depressions (e.g. the Pre-Caspian, Dnieper and Pechorian depressions).

The sedimentary cover of the platform is composed of deposits of Cambrian to Quaternary age. Palaeozoic sediments are most common. Various stratigraphical units contain sulphate and sulphate-carbonate assemblages (gypsum and anhydrite interbedded with limestone and dolomite) (Fig. 1). Sulphate rocks underlie more than 80% of the entire region. Most extensive are the sulphate and sulphate-carbonate rocks of the Lower Permian (2.4 million km^2), Upper Permian (1.5 million km^2), Carboniferous (1.0 million km^2)) and Devonian (0.6 million km^2). Sulphates are less common within the Jurassic (150,000 km^2), Ordovician and Silurian (100,000km^2) and Neogene (35,000km^2). They are negligible within Cretaceous and lacking within Cambrian, Triassic and Palaeogene sequences. The above sequence areas are partially superimposed.

However, the areas where sulphate rocks crop out at the surface, or occur in relatively close proximity to it (within the upper 100-150m), are much smaller (Fig.2). Gypsum karst is most strongly developed and best manifested at the surface within these areas.

In almost all the areas where gypsum karst is manifested to the surface, it is developed within Palaeozoic rocks, particularly in the Devonian (in the Baltic republics and Timan ridge) and Permian successions (the northern, central and eastern parts of the EEP, pre-Caspian lowland and Donetzk Basin). Karst in Ordovician, Silurian, Jurassic and Cretaceous gypsum is documented only in deep-seated occurrences, without any surface expression. In the Western Ukraine (the Podol'sko-Bukovinsky region) gypsum karst has developed within Neogene rocks and displays distinctive characteristics in terms of both underground and surface forms.

As illustrated by Figure 1, gypsum karst within the EEP is associated predominantly with old, mainly Permian formations. Only the gypsum of the Western Ukraine is the product of relatively recent evaporite formation within the Para-Tethys zone. In the Palaeozoic successions sulphate rocks are represented commonly by quite thick (80-120m) sulphate-carbonate and sulphate-argil-

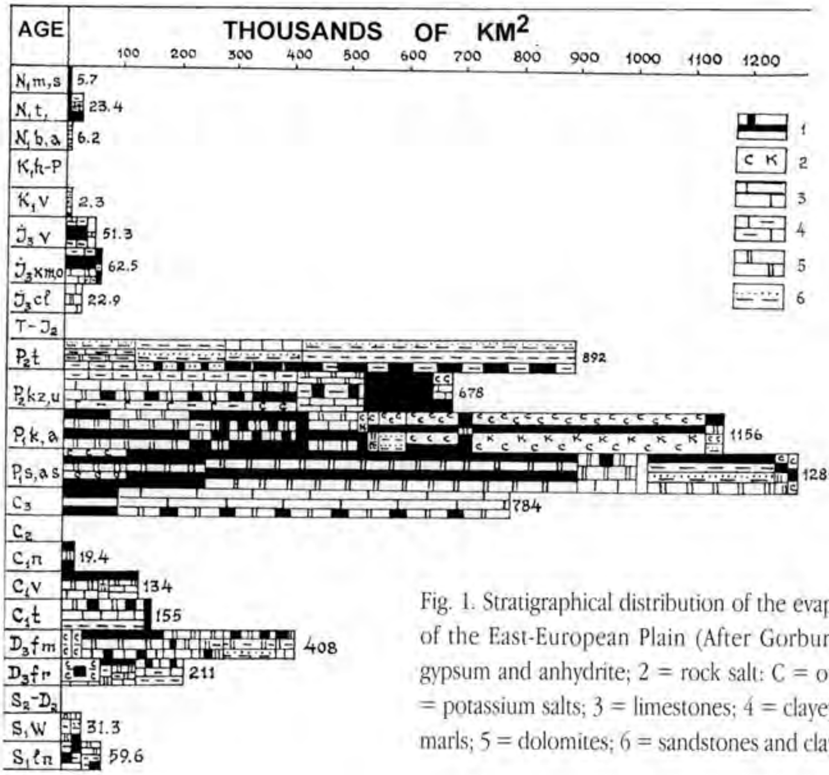

Fig. 1. Stratigraphical distribution of the evaporite formations of the East-European Plain (After Gorbunova, 1977): 1= gypsum and anhydrite; 2 = rock salt: C = other chlorides, K = potassium salts; 3 = limestones; 4 = clayey limestones and marls; 5 = dolomites; 6 = sandstones and clays.

laceous units, comprising gypsum and anhydrite intercalated with dolomite, limestone, clay, marl and salt. The sulphate rocks normally have a cryptocrystalline or finely-crystalline structure. Because the rocks are well stratified and have experienced repeated cycles of tectonic activity and karstification, the sequences are heavily fractured and locally brecciated. In contrast, the Neogene gypsum in the Pre-Carpathian region is characterised by lithological homogeneity, occurring as a single bed (10-40m), surrounded by non-evaporitic sediments. This gypsum has a mainly coarsely-crystalline heteroblastic structure, which is the result of re-crystallisation and alteration of the rock in the vertical direction. Tectonic discontinuities are discrete and do not cause severe disruption of the gypsum, although they do separate the strata into large blocks

Differences in the lithology, structure and age of the Palaeozoic and Neogene sulphate sequences, (along with other factors, such as depth of occurrence, presence of cover beds, relief etc.) largely determine locally important distinctive characteristics of the karst within corresponding regions of the EEP. The prolonged and complex history of tectonism, geomorphic development and karstification in gypsum karst regions upon the Palaeozoic sequences (such as the Pre-Urals) is responsible for the common occurrence of filled cavities and an abundance of other palaeokarst features, for the generation of regionally extensive 5-30m-thick sequence of karst breccia, capping or replacing the gypsiferous formation, and for the presence of large, polje-like,

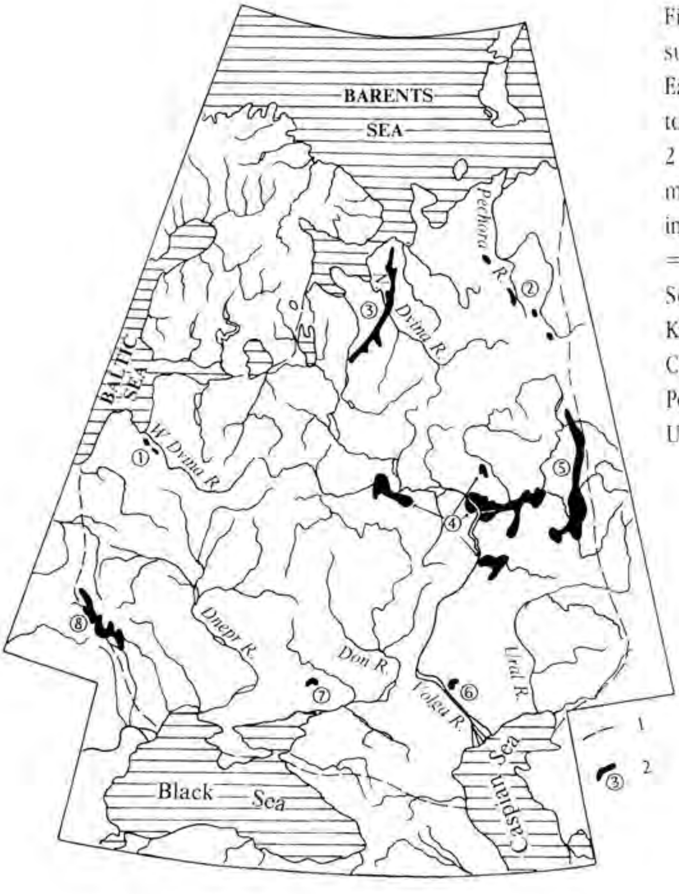

Fig. 2. Main regions of surface sulphate karst displays on the East-European Plain: 1 = contour of the East-European Plain; 2 = areas of intense development of gypsum karst. Numbers indicate the following regions: 1 = Baltic, 2 = Timan, 3 = Pinego-Severodvinsky, 4 = Volgo-Kamsky, 5 = Pre-Urals, 6 = Pre-Caspian, 7 = Donetsk, 8 = Podol'sko-Bukovinsky (Western Ukraine).

depressions and dissolution troughs filled with Neogene sediments.

In the Pre-Carpathian region (Western Ukraine) the karst is related to a single uplift cycle and is characterised by a relatively clear structural guidance, the presence of well-preserved and extensive maze cave systems, and a "simplicity" and uniform style of surface karst landforms.

The differences specified above are generally applicable throughout the EEP. However, when considered in detail, each gypsum karst region, even different karsts that have developed upon formations of the same-age, has many distinctive features, determined by local geological, geomorphological and hydrogeological settings.

There are many published works devoted to the gypsum karst of different regions of the EEP, but only two of them provide reviews of the whole plain (Rodionov, 1963; Gorbunova, 1977). Rodionov differentiated karst regions on the basis of their relationships to large tectonic structures, and considered both carbonate and sulphate karst within the specified regions. Gorbunova focused specifically on gypsum karst and made a regional division based upon the occurrence of evaporitic formations. Thus, the two schemes differ considerably. The regional division adopted in

Table.

Geological settings of the main gypsum karst regions of the Eastern-European plain

Karst region	Stratigraphical index of gypsiferous formations	Lithological associations	Typical thickness of main gypsum beds (total thickness of the formation), m	Tectonic setting, the type of gypsum occurrence	Lithology and thickness of the overburden, m
1. Baltic	D_3 fm	Sulphate -carbonate - clayey	10-20 (40)	Latvian saddle, stratified, horizontal	Sands, clay, 10-50
2. Timansky	P_1 k D_3	sulphate - carbonate, sulphate -carbonate -clayey	5-20 (30)	Timan high, stratified, gently-inclined (2-6°)	Loams, alluvium, 5-30
3. Pinego-Severo-dvinsky	P_1	sulphate - carbonate	20-30 (80-120)	Moscow syncline, stratified, horizontal	Loams, sands, aleurolites, 0-30 and more
4. Volgo-Kamsky	P_1 k P_2 a P_3 s	sulphate, carbonate - sulphate	10-20 (60-65)	Moscow syncline, stratified, horizontal	Loams, sand, argillites, 0-100 and more
5. Pre-Ural	P_1 k	Sulphate - carbonate	10-20 (100-120)	Highs and depressions of the east flank of the East-European Platform, stratified, monoclinal (3-5°) and brachy-folded	Loams, sandstones, argillaceous sediments, 0-60
6. Pre-Caspian	P_1 k	Sulphate - clayey, sulphate-salt	40-50 (40-100)	Gypsum caprocks of salt domes	Loams, clays, pebbles, 0-10 and more
7. Donetsk	P_1	Clayey -sulphate, sulphate - carbonate -clayey	15-20 (60-100)	Donetsk depression, stratified, horizontal	Sands, clays, limestones, 0-60 and more
8. Podol'sko-Bukovinsky	N_1 bd	Sulphate	20-40	South-west flank of the East-European Platform, Carpathian foredeep, stratified, horizontal to gently-dipping (2-4°)	Clays, marls, limestones overlying the gypsum 5-100

this paper attempts to combine elements of both approaches and is simplified to provide a convenient framework within which to compare the characteristics of the individual regions. Eight main karst regions (see Fig.2 and Table) are distinguished, within which gypsum karst is present at the surface and is characterised by specific karst type assemblages, not only by "hidden", deep-seated, intrastratal karst. Within each region it is possible to identify several (up to 5) karst areas where a gypsum karst of particular type predominates.

2. Regional overview

Some of the important gypsum karst areas within the EEP are described in detail in separate chapters of this volume. The overview below is intended to provide a brief comparative picture of the entire region, with special emphasis on those areas that are not covered by other chapters.

2.1. The Baltic region

The region is located in the northwest part of the EEP. An Upper Devonian gypsiferous formation occur in the shallow sub-surface or at outcrop within several small (7-113km^2) areas. The formation comprises two 15-20m-thick beds of gypsum. Another, the Narva formation, consist of intercalated, relatively thin (0.3-3m) layers of gypsum, clays and dolomites and never crops out.

Gypsum karst settings represented in the region include subjacent intrastratal and entrenched karst types. Surface karst features (collapse and subsidence dolines, karst lakes) are best developed where the overburden thickness does not exceed 20-25m. In some localities the density of karst forms reaches 200 units per km^2. Karst forms in many places are related to upward discharge of confined or semi-confined aquifers. The presence of H2S in water emerging from many springs and boreholes indicates that sulphate reduction processes are active in the source aquifers. Caves are uncommon. A detailed account of gypsum karst of the region is presented in Chapter II.10.

2.2. The Timansky region

The region encompasses numerous areas of subjacent intrastratal and denuded karst, with areas of deep-seated gypsum karst between, lying within the extensive Timansky ridge, a Riphean folded structure that stretches across the northeast part of the Eastern-European Platform from the northern Urals to the Arctic Ocean. Crystalline basement rocks crop out in the central parts of the ridge. Palaeozoic formations, which contain beds (up to 20-27m) of sulphates, occur on the slopes of the uplift, and are complicated by gentle linear and dome-like folds.

Gypsum karst is developed in Devonian (Frasnian; single gypsum beds) and Lower Permian (Kungurian; intercalated gypsum, dolomite and limestone beds) rocks Where gypsum occurs at shallow depth dolines and blind valleys are common. In the Vym' river basin there are areas with a very high density of karst landforms, resembling badlands topography. Deep-seated and subjacent intrastratal gypsum karst is recorded in the gypsum mining area along the Izhma river, where the Devonian gypsiferous formation is up to 100m thick (Lysenin & Sosnovskaya, 1974). Boreholes and mines have intercepted numerous cavities yielding sulphate-rich water (TDS contents 2.1-2.4 g/L). The mine experienced karst water inflow that increased from 1,700 m^3/day in 1959 to 20,000 m^3/day in 1965. This inflow supposedly developed due to leakage from the nearby river, and eventually led to abandonment of the mine. The total water withdrawn in 1961-1965 was 8,820,000m^3.

In general, the gypsum karst of this extensive taiga region is as yet poorly studied. The available data are derived from the works of Ljubimov (1959), Torsuev (1964, 1975), Rodionov (1963) and Lysenin & Sosnovskaya (1974).

2.3. The Pinego-Severodvinsky region

This is one of the largest integrated gypsum karst regions in Europe, located in the north of European Russia. It stretches more than 1,000km from south to north as a relatively narrow belt (10-50km wide), almost reaching the Barentz Sea coast. The Severnaja Dvina river dissects the middle of this belt. Sulphates are represented by Lower Permian gypsum and anhydrite. South of the Severnaja Dvina the sulphates are intercalated with dolomites and limestones, and to the north the gypsum and anhydrite form a relatively homogenous sequence 80-120m in thickness. Karst development is most prominent within the latter area, which is also known as the Belomorsko-Kulojsky Plateau.

Gypsum karst is represented by intrastratal entrenched and denuded sub-types. Surface karst morphology includes a great variety of forms, including different types of dolines, shafts, gorges, canyons, blind valleys and large depressions. The remarkable karst hydrology includes rivers and smaller streams with underground and surface course sections, karst lakes, springs, and so on. Locally, there are karst fields with an extremely high density of different landform types, some of which are 20-50m deep. As these are covered by taiga forest the area represents almost impassable terrain.

There are about 150 known caves in the region, with some 50km of mapped passages. 22 caves are longer than 1 km. The Kulogorskaja-1-2-Troja system is the longest gypsum cave in the world outside the Western Ukraine, with a length of 14,100m. Most of caves display linear or crudely dendritic patterns, although maze patterns are also common. Some caves have up to 4 storeys.

The gypsum karst of the region is described in detail in many published works, of which the more important include Torsuev (1964), Chikishev (1966), Saburov (1974), Caves... (1974) and Malkov et al (1986, 1988).

2.4. The Volgo-Kamsky region.

This region lies in the central part of the EEP, in the basins of the Middle Volga and Kama, and corresponds to the Volgo-Ural syncline. Within the region four relatively large gypsum karst areas are distinguished according to their major prominent tectonic structures: Gorkovsky, Nizhnekamsky, Zhigulevsky and Vjatsky.

Karst is developed in a Lower Permian formation, in which 10-45m-thick gypsum beds are intercalated with limestones and dolomites. The formation is overlain by karstified limestones and dolomites, and sequences of terrigenous (poorly pervious) marls, argillites and sandstones, and/or glacio-fluvial (highly-pervious) sands. The prevailing karst development settings represent deep-seated and subjacent intrastratal karst.

Surface karst features develop in areas where the thickness of the terrigenous overburden is least (less than 40-50m), or where the overburden is represented by unconsolidated permeable sands, even if their thickness is great (up to 100m). In the former case, deep pit-like or pot-like collapse dolines predominate, while in the latter areas cone karst suffosional dolines are more common. The density of dolines recorded in some localities can be very high (93 or even 261 units per km^2). There are also some large flat-floored karst depressions, dry valleys, karst lakes and springs, commonly discharging sulphate-rich water from deep-seated confined and semi-confined aquifers. Drilling data supply many recordings of cavities and brecciated zones within the gypsiferous formation.

The main works that deal with the gypsum karst of this region include: Iljin et al. (1960), Karst phenomena... (1960), Problems... (1962) and Stupishin (1965, 1967).

2.5. The Pre-Ural region

The region is located in the east of the plain. In the tectonic context it corresponds to the eastern flank of the platform and to the adjacent Ural foredeep. Sulphate rocks occur at relatively shallow depth (within the upper 100-150m of the preserved geological column) across an area of 37,000km^2 (Maximovich & Kostarev, 1973). The 100-120m-thick sequence of gypsum and anhydrite of the Lower Permian Kungurian Member includes some limestone and dolomite beds (commonly 2-5m thick). The outcrop of the gypsiferous formation stretches from north to south as a 10-20km-wide belt that widens in the southern (Bashkiria) part.

An erosional network is incised to different depths into the sulphate-carbonate sequence, locally cutting the full thickness and dividing the succession into isolated massifs. Consequently, the karst sub-types represented in the region range from deep-seated intrastratal karst through subjacent and entrenched, to denuded karst.

The most intense karst development is observed in the vicinity of river valleys, and within surface watersheds where the overburden thickness is reduced. Regionally, the most karstified areas correspond to the axis of the "sulphate belt", as westward and eastward the formation is buried by terrigenous sediments to considerable depths. Doline density reaches values of 500 units per km^2 locally. Other karst landforms include trenches, blind and/or dry valleys and large depressions. There are more than 200 known gypsum caves, the largest being the 5,600m-long Kungurskaya Ledjanaja (Kungur Ice Cave). Karst hydrology is represented by underground rivers and many karst springs, with discharges ranging up to 200 L/s.

Gypsum karst development in the region has a long and complex history dating back up to Mesozoic. Its earlier features include large depressions filled with Neogene sediments, whose floors lie 50-60m below the levels of modern valleys. Prolonged karst development has resulted in the formation of a 5-30m-thick cover of brecciated material overlying the remaining gypsum. Along the axes of structural uplifts, such as the Ufimsky dome, such breccia entirely replaces the gypsiferous formation. Karst breccia horizons are also recorded commonly within the formation.

The gypsum karst of the region has had considerable effect upon economic activity, and in turn, there has been a strong human impact upon the karst (see Chapter I.11).

Gypsum karst has been well-studied in the region; several hundred publications are devoted to it. Most important among these are: Gorbunova (1965, 1977), Gorbunova et al. (1992), Lukin (1964), Lukin & Ezhov (1975), Martin (1973), Maximovich & Gorbunova (1958) and Pechorkin (1969). A more detailed account of the gypsum karst of the region is presented in Chapter II.11.

2.6. Pre-Caspian region

This extensive region lies on the south-east side of the EEP, and is also known as the Pre-Caspian lowland. In the tectonic respect it represents a depression filled with thick (3 to 5km) sedimentary deposits. Some 1500 salt diapirs (domes) are known throughout the region. The dome arches normally lie at depths ranging from 200 to 1500m but locally their overlying gypsum rocks (the Lower Permian Kungurian Member) and underlying salts crop out at the surface. Some domes are topped by secondary gypsum caprocks, up to 100m thick. In fact, there are several tens of isolated gypsum karst "islands" throughout the region, ranging in area from 50 to 300km^2.

The characteristics of the karst are determined mainly by the depth of occurrence of the sulphate rocks. They are commonly karstified from the surface, although some deep-seated karst features are recorded that are associated with saline waters. In the Chelkarsky dome, karst cavities have been intercepted by boreholes at depths up to 350m At the gypsum/salt contact some boreholes yielded up to 2.5 L/s of Cl-Na-Ca-SO_4 water.

Gypsum karst in the region is described in Gedeonov (1947), Gvozdetsky (1953), Korobov & Polenov (1964), and Sotnikov & Arkhidjakonskikh (1974).

2.7. The Donetsk region

This comparatively small region (about 2,000km^2) is located on the south of the EEP, within the Donetzk depression, where salt and sulphate rocks of the Lower Permian evaporite formation are present. The following sequence types are distinguished: clayey-anhydrite, salt, gypsiferous with dolomites, and terrigenous. Gypsum karst is reported in areas where sulphate rocks lie at shallow depths or crop out at the surface. Dolines are associated mainly with gypsum karst, and large depressions are believed to have originated due to dissolution of salts. Within such depressions the gypsum beds are heavily broken and brecciated. In areas where gypsum beds up to 60m thick are intact, caves are reported to have been intercepted by gypsum mines. In the Pshenichny deposit, the average ratio of area of cavities in the workings to the area of intact original rocks is 17.5%. The largest known cave, which is 150m long, displays phreatic morphology.

The gypsum karst of the region is described in the works of Khod'kov (1955), Kozintzhev (1971) and Klimchouk & Rogozhnikov (1972).

2.8. The Podol'sko Bukovinsky region

The region is situated on the southwest side of the EEP, stretching along the junction between the platform and the Carpathian foredeep. The extensive 10 to 40m-thick gypsum bed of Miocene (the Upper Badenian Member) is intensely karstified. It is underlain by Lower Badenian sandy-carbonate sediments and overlain either by limestones and argillaceous limestones, or by thick (up to 100m or more) Sarmatian clayey sequences. The total area of the gypsum karst is about 20,000km^2.

Karst development began under deep-seated artesian conditions during the Late Pliocene. Owing to differential uplifts during the Late Pliocene to Pleistocene and a consequent deep incision of major valleys, the current karst development settings vary between three sub-parallel zones, which represent deep-seated, subjacent and entrenched types of karst. Surface karst morphology and hydrogeological features differ considerably between these zones. In the entrenched zone and, to some extent, in the subjacent karst zone, giant relict maze caves have been explored. Five of these hold the highest ranks in the list of the world's longest gypsum caves. The longest cave, Optimisticheskaja, is now more than 200km long.

The gypsum karst of the region is well-studied, with several hundred published works. The most important of these are those of Ivanov (1956), Ivanov & Dubljansky (1966), Dubljansky & Ivanov (1970), Dubljansky & Smol'nikov (1969), Andrejchuk (1984, 1988), Klimchouk & Andrejchuk (1986, 1988), Klimchouk & Rogozhnikov (1982), Klimchouk et al. (1985, 1988, 1995), Klimchouk (1986, 1990, 1992). For more detailed discussion of this region see Chapter II.9.

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Chapter II.9

GYPSUM KARST IN THE WESTERN UKRAINE

Alexander Klimchouk

Introduction

The great gypsum karst of the Western Ukraine, which is associated with Miocene (Badenian) gypsum, provides the world's foremost examples of intrastratal gypsum karst and speleogenesis under artesian conditions. Differential neotectonic movements have resulted in various parts of the territory displaying different types (stages) of intrastratal karst, from deep-seated, through subjacent, to entrenched.

Internal gypsum karstification proceeded mainly under confined hydrogeological conditions. While such development still continues in part of the territory, other parts exhibit entrenched karst settings. Huge relict maze cave systems have been explored here, five of which are currently the longest known gypsum caves in the world. They account for well over half of the total length of gypsum cave that has been explored. This unique concentration of large caves reflects the local coincidence of specific structural prerequisites of speleogenesis (character and extent of fissuring), favourable regional evolution (rapid uplift, and fossilization of maze systems), the presence of overlying limestone aquifers, and a widespread clayey protective cover (which prevented the total infilling and/or destruction of the caves). Surface karst evolved as a consequence of the internal karstification in the gypsum, and the karst landform assemblages differ between the territories that present different types of karst.

Important previous works on the gypsum karst of the region include Ivanov (1956), Ivanov & Dubljansky (1966), Dubljansky & Ivanov (1970) and Dubljansky & Smol'nikov (1969). Abundant new data and their interpretation were developed during the nineteen-eighties and nineteen-nineties, and presented mainly in publications by Andrejchuk and Klimchouk.

1. Geological setting

The Miocene gypsum sequence is widespread along the southwestern edge of the Eastern European Platform, in the transition zone between the platform and the Carpathian foredeep. Gypsum stretches from the northwest to southeast for about 300km as a belt ranging from several kilometres to 40-80km wide (Fig. 1). The present extent of sulphates on the platform is about 20,000km^2.

Most Miocene rocks along the platform margin overlie eroded Cretaceous strata, which include terrigenous and carbonate sediments, mostly marls and sandstones, together with detrital and argillaceous limestones. The Miocene succession comprises deposits of Badenian and Sarmatian age. The Lower Badenian "member", beneath the gypsum, includes mainly carbonaceous, argillaceous and sandy beds (70-90m thick) adjacent to the foredeep, and these grade into rocks of calcareous bioherm and sandy facies (10-30m thick) towards the platform interior.

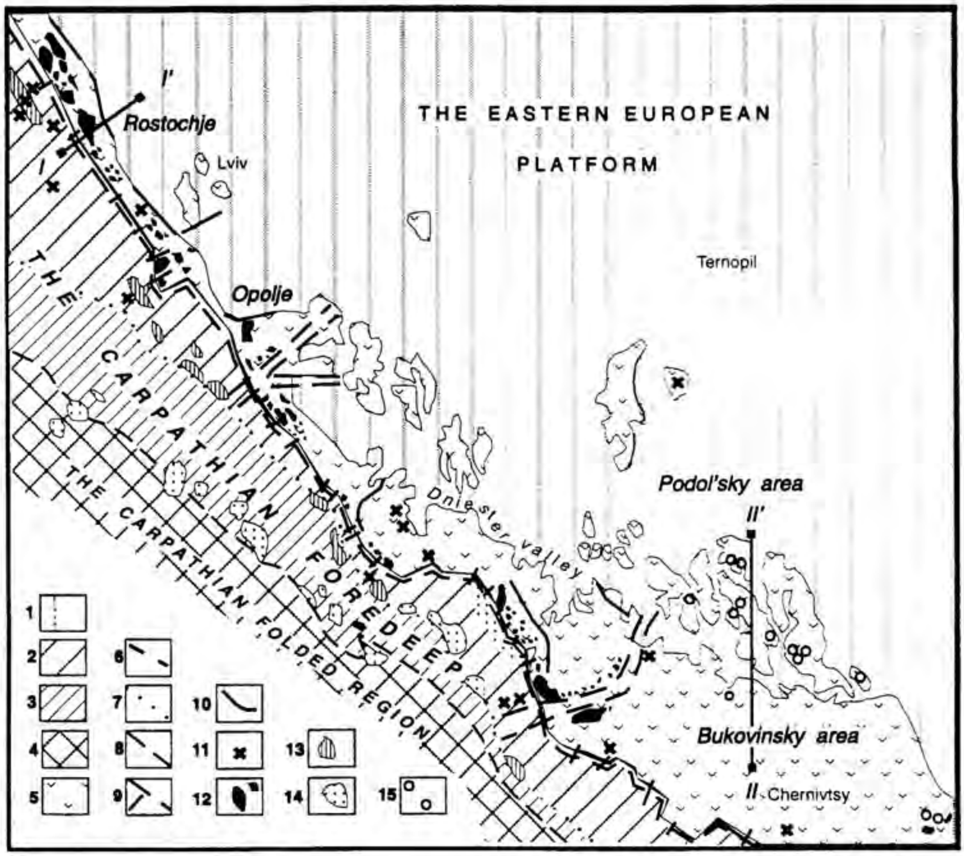

Fig. 2. Location of the gypsum stratum, sulfur deposits, and large caves in the Western Ukraine (modified from Polkunov, 1990). 1 = Eastern-European platform fringe. Carpathian foredeep: 2 = outer zone, 3 = inner zone. 4 = Carpathian folded region; 5 = sulfate rocks on the platform. Tectonic boundaries include: 6 = platform/foredeep, 7 = outer/inner zone of the foredeep, 8 = foredeep/folded region. 9 = other major faults; 10 = flexures. 11 = sulfur mineralization; 12 = sulfur deposits; 13 = gas deposits; 14 = oil deposits; 15 = large maze caves in the gypsum.

The gypsiferous sequence (10-40m thick) is variable in structure and texture. In the Podol'sky area, it includes three units, which, in an ascending order, contain crypto- and microcrystalline massive gypsum, bedded microcrystalline gypsum and mega-crystalline gypsum. Gypsum within the upper unit displays large spherulitic structures (Klimchouk, Andrejchuk & Turchinov, 1995). Close to the foredeep, the gypsum is more homogeneous and aphanitic in texture, and the anhydrite content of the sequence increases. There are sporadic thin interbeds of carbonate and clay.

A layer of micritic and cryptocrystalline limestone, ranging from several tens of centimetres to more than 25m in thickness, overlies much of the gypsum. This limestone contains two genetic varieties that differ in carbon isotopic composition. The micritic limestone (locally called

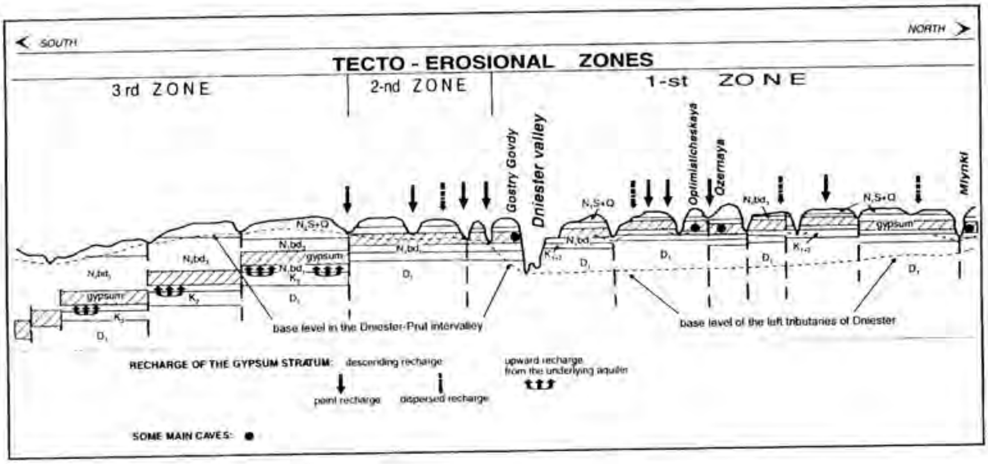

Fig. 2. Geological and hydrogeological settings of gypsum karst development in the Podol'sky and Bukovinsky areas in the south-eastern section of the gypsum belt (line II-II' on Fig. 1 and A-B on Fig.3) (After Klimchouk & Andrejchouk, 1988).

"Ratynsky") has normal "evaporitic" $\delta^{13}C$ values. The other variety, which is crypto- and microcrystalline, was formed epigenetically by replacement of the gypsum during sulphate reduction, and is characterized by "light" carbon, with $\delta^{13}C$ from -32 to -65 ‰. Where the limestone thickness exceeds 1 to 2m, it consists of mainly epigenetic calcite, which locally replaces the gypsum stratum entirely. Together this limestone and the gypsum comprise the Tyrassky Formation.

The Tyrassky Formation is overlain by the Upper Badenian "member", which begins with argillaceous and marly lithotamnion limestones (the Ternopol'sky' beds, 1.5 to 3m thick). Above this is a succession of clays and marls, with its lower part in the Upper Badenian (the Kosovsky Formation), and its upper part in the Lower Sarmatian. The total thickness of clay sediments is 40 to 50m in the Podol'sky area, reaching 80 to 100m towards the foredeep, and thickening to several hundred metres close to the regional growth faults that separate the platform edge from the foredeep.

The Miocene succession is overlain by late-Pliocene and Pleistocene glacio-fluvial sands and loams in the north-west section of the gypsum belt, and by sand and gravel alluvial terrace deposits left by the pre-Dniester river during the late Pliocene and early Pleistocene in the Podol'sky area. Many buried valleys, of early to mid Pleistocene age, are entrenched 30 to 50m into the Kosovsky and Sarmatian clays and, locally, into the upper part of the Tyrassky Formation.

The present distribution of the Miocene formations and the levels of their denudation vary in a regular way from the platform interior towards the foredeep (Andrejchouk, 1988; Klimchouk et al, 1985; Klimchouk & Andrejchouk, 1988). The Tyrassky Formation dips 1 to 3° towards the foredeep and is disrupted by block faults in the transitional zone. To the south-west of the Dniester valley, large tectonic blocks drop down as a series of steps, the thickness of clay overburden increases, and the depth of erosional entrenchment decreases (Fig. 2). This variation, the result of differential neotectonic movement, played an important role in the hydrogeological evolution of the Miocene aquifer system. They determined the recharge-discharge and flow conditions, and hence helped to guide the development of karst in the gypsum.

2. Hydrogeological setting and karst types

In hydrogeological terms the region represents the south-western portion of the Volyno-Podolsky artesian basin (Shestopalov, 1989). Sarmatian and Kosovsky clays and marls provide an upper confining sequence and the Tyrassky Formation carbonate (above the gypsum) and the Lower Badenian sandy carbonate beds (below the gypsum) are aquifers. The hydrogeological role of the gypsiferous unit has changed with time, from initially being an aquifuge, intervening between two aquifers, to a karstified aquifer with well-developed conduit permeability. Underlying Cretaceous sediments have variable properties across the area. Regional flow is from the platform interior, where clayey formations and the gypsum beds are largely denuded, toward the large and deep Dniester valley and the Carpathian foredeep. The main factors that determine contemporary hydrogeological conditions are the differences in the depths of gypsum occurrences and the extent of erosional entrenchment by the major valleys. Three sub-parallel zones are distinguished, each characterized by a different type of gypsum karst (see Fig.2).

2.1. The first zone: entrenched karst

In the 1st zone the Miocene rocks and underlying formations are deeply entrenched by valleys of the major left bank sub-parallel tributaries of the Dniester, separated by wide inter-valley massifs where the gypsum and clay overburden remain largely intact. The Miocene formations are almost entirely drained and only in the central parts of the inter-valley massifs do the sub-gypsum units contain unconfined underground waters. In some tectonic blocks the water table extends upwards into the lower part of the gypsum (Ozernaya Cave) with multi-year fluctuations that range from 3 to 5m. Huge maze cave systems in the gypsum are relict, having formed under formerly artesian conditions. Modern dissolution is restricted to the lower part of gypsum, where the water table is present, at points of focused vertical percolation (where vertical dissolution pipes develop) and along linear underground streams that are fed via swallow holes that receive periodic surface flow.

Superficial karst landforms on the inter-valley plateaux are represented by relatively scarce large dolines with swallow holes, blind valleys and smaller recent collapse dolines. Dolines are formed mainly by means of the vertical through structure (VTS) mechanism, which is triggered by the development of vertical dissolution pipes. Initial collapse dolines evolve into large cone-shaped forms with swallow holes in their floors, or into blind valleys, if they intercept a sufficiently large amount of surface runoff. Focused point recharge is the main recharge mode of the Miocene aquifer in this zone. Doline density increases locally where the capping clays are removed, as within old, high, river terraces. Discharge takes the form of springs outflowing from the sub-gypsum unit, or from the underlying Cretaceous formations.

These conditions typify an intrastratal entrenched karst, according to the classification introduced in Chapter I.4. They are characteristic of the area within the interior of the platform, to the north-east and north of the Dniester valley, and for the Podol'sky area in particular. A narrow area on the right bank of the Dniester valley also lies within this zone, but this grades into the 2nd zone deeper into the Dniester-Prut inter-valley.

2.2. The second zone: subjacent karst

To the south-west and south of the Dniester valley the depth of gypsum occurrence increases, and the depth of erosional entrenchment diminishes. The narrow (3 to 15km-wide) 2nd zone is distinguished in the Dniester-Prut inter-valley, where the water table lies within the gypsum or locally within the higher unit. Floors of erosional valleys lie above, or are entrenched into, the gypsum unit, causing diversified karst hydrography to develop, with intermittent streams, swallow holes, and ascending and descending springs. Collapse and subsidence dolines are common, as the water table and localized streams operating within the gypsum intensify breakdown processes by active dissolution and erosional removal of cave fills. Cave systems inherited from the confined stage are accessible only in small fragments, but their wide presence is implied by drilling data and observations in the neighbouring 1st zone, where the gypsum is drained and has been extensively quarried. Relatively small linear through caves are also common, and their origin is attributed to erosion under modern conditions.

In general the groundwater flow in the Miocene aquifer is directed northwards to the Dniester valley, and south-southwestwards to the Prut valley. Flow becomes confined in the latter direction, within the 3rd zone, where the Tyrassky Formation lies at an even greater depth beneath the increasing thickness of clayey overburden. The 2nd zone represents subjacent karst conditions, grading locally into early phases of entrenched karst.

2.3. The third zone: deep-seated and subjacent karst

The 3rd zone stretches along the boundary between the platform and the foredeep. Within this zone the Miocene aquifer formations lie at considerable depths beneath the Kosovsky clays, which are cut only by shallow erosional valleys, so that flow is confined.

Recharge conditions differ between a narrow north-west and a wider south-east section of the gypsum belt. In the north-west, recharge occurs within the adjacent unconfined area (where both the clays and the gypsum are denuded), by infiltration directly into the sub-gypsum beds. In the south-east of the gypsum belt recharge occurs from the neighbouring area of subjacent gypsum karst (the 2nd zone), via karst systems.

On the opposite flank of the confined flow area, along the foredeep margin, regional faulting has brought the Miocene aquifer into lateral contact with an even thicker Kosovsky clayey sequence, so that further flow in this direction is prevented and upward discharge occurs locally, focused upon areas where the confining properties of the Kosovsky clays are weakened by stratigraphical or tectonic discontinuities, or incised erosional valleys. The latter situation is common in the north-west part of the gypsum belt, where discharge is commonly focused along buried valleys, and in the south-east section, where discharge converges towards the major modern Prut valley.

Lower Badenian sandy-carbonaceous sediments that lie immediately below the gypsum provide the major aquifer. Erroneously the gypsum unit was long considered as being an aquifuge separating the sub-gypsum and supra-gypsum aquifers; numerous indications of karstification in the gypsum were incorrectly interpreted. However, it has recently been shown (Klimchouk, 1990, 1992, 1997a) that extensive karst systems develop in the gypsum due to the effects of upward cross-formational hydraulic communication between the early aquifers, with the gypsum providing the hydraulic connection (see section 3.2 below). Such systems, which are modern analogues of relict maze caves that are known in the 1st zone, develop preferentially in areas of potentiometric lows, where an overall discharge from the artesian aquifer system occurs. Analysis of data on the many cavities intercepted in the gypsum by exploratory drilling in different deposits, suggests that their morphology and structure are similar to those of explored relict caves (Klimchouk, 1997a,b).

Gypsum karstification within the 3rd zone is not manifested to the surface across most of those areas where the clayey overburden thickness exceeds 45 to 60m; this represents an zone of deep-seated karst. However, in areas where the natural groundwater circulation has been affected by an anthropogenic impact (such as opencast quarrying or groundwater abstraction) and karst processes have consequently been intensified in the gypsum, collapse and subsidence dolines may develop at the surface, being induced by karstification in the gypsum at still greater depths (see Chapter I.10). Moreover, there are "azonal" areas within the 3rd zone, related particularly to the most uplifted tectonic blocks, where the gypsum lies at relatively shallow depths and major valleys have incised into it, breaching artesian confinement (as in the Krivsky and Mamalyzhsky blocks in the Bukovinsky sub-region; Andrejchuk, 1988). Locally this results in drainage of the upper part of the gypsum unit, and widespread development of collapse and subsidence phenomena. Thus, such cases correspond to subjacent karst conditions.

3. Caves and their genesis

3.1. General characteristic

Fourteen large caves are known in the region, with development exceeding 1km. Eleven are north of the Dniester valley, within the Podol'sky sub-region, and nine of these caves lie within a narrow belt sub-parallel to the Dniester valley. Two caves (Mlynki and Ugryn') are outside this belt, some 15 to 20km to the north. All of these caves are within the 1st zone, as is one more cave, Gostry Govdy, on the right bank of Dniester. Two other large caves, Zolushka and Bukovinka, are situated in the Bukovinsky sub-region, near Prut river, in the area of artesian flow within the Miocene aquifer system (3rd zone), but within the "azonal" area comprising the most uplifted blocks, where the upper part of the gypsum has been entrenched and drained. Because of this, water table conditions prevail in the gypsum unit within this area. In the area of Zolushka Cave, additional water table lowering has been caused by groundwater abstraction related to quarrying (see Chapter I.10).

All the large gypsum caves in the region are mazes developed along of vertical and steeply inclined fissures and arranged into laterally extensive networks. Aggregating passages form lateral

Table

Parameters of large caves and cave fields

Cave name	Extent (m)	Specific volume (m^3 m^{-1})	Passage density, (km km^{-2})	Coefficient of karstification, (% area)	Coefficient of karstification, (% volume)
The Podol'sky sub-region					
1 Optimisticheskaja	200,000+	2.6	298	38	4
2 Ozernaja	117,000	6	173	51	6
3 Mlynki	25,000	3.3	123	24	3
4 Kristalnaja	22,000	5	161	28	7
5 Slavka	9,100	3.8	118	24	3
6 Verteba	7,820	6	206	61	12
7 Atlantida	2,525	4.5	168	30	4
8 Ugryn	2,120	3.8	193	36	7
9 Jubilejnaja	1,500	2.3	277	37	4
10 Komsomolskaja	1,244	2.1	124	17	3
11 Dzhurinskaja	1,135	2.3	126	18	2
The Bukovinsky sub-region					
12 Zolushka	92,000	8	208	71	6
13 Bukovinka	2,408	2.5	321	57	4
14 Gostry Govdy	2,000	1.6	272	27	4
Totals	477,852	–	–	–	–
Averages	–	3.8	198	37	5

two- to four-storey systems that occupy areas of up to 0.8km^2. Significant morphological parameters of the caves are summarized in the Table, and some typical cave patterns are illustrated by Fig.3.

Optimisticheskaja Cave is the longest gypsum cave, and the second longest cave of any type, known in the world, with more than 200km of surveyed passages. The region holds the five longest known gypsum caves in the world, accounting for well over half of the total known length of gypsum caves. By area and volume the largest caves are Ozernaja (330,000m^2 and 665,000m^3) and Zolushka (305,000m^2 and 712,000m^3), followed by Optimisticheskaja Cave (240,000m^2 and 500,000m^3).

The absolute parameters of cave systems and their fields are subject of change, depending upon exploration efforts; they grow constantly during the course of speleological exploration. Specific parameters are more informative. Specific volume (the volume/length ratio) characterizes "voluminousness" of cave passages in a certain cave system. For the caves of the region this feature range from 1.6 (Gostry Govdy Cave) to 8.0 (Zolushka Cave) m^3 m^{-1}; the average for the region is of 3.84 m^3 m^{-1}.

Passage network density is characterized conveniently by use of the ratio of cave length to the unit area of a cave field (km km-2). This parameter varies for the region from 118 (Slavka Cave) to 321 (Bukovinka Cave) km km-2, with the average value of 198 km km-2.

The availability of detailed morphometrical data on caves and the host rock bodies allows the calculation of coefficients of karstification of the gypsum stratum both in terms of area and volume. The former parameter varies from 17% (Komsomol'skaja Cave) to 71% (Zolushka Cave). High

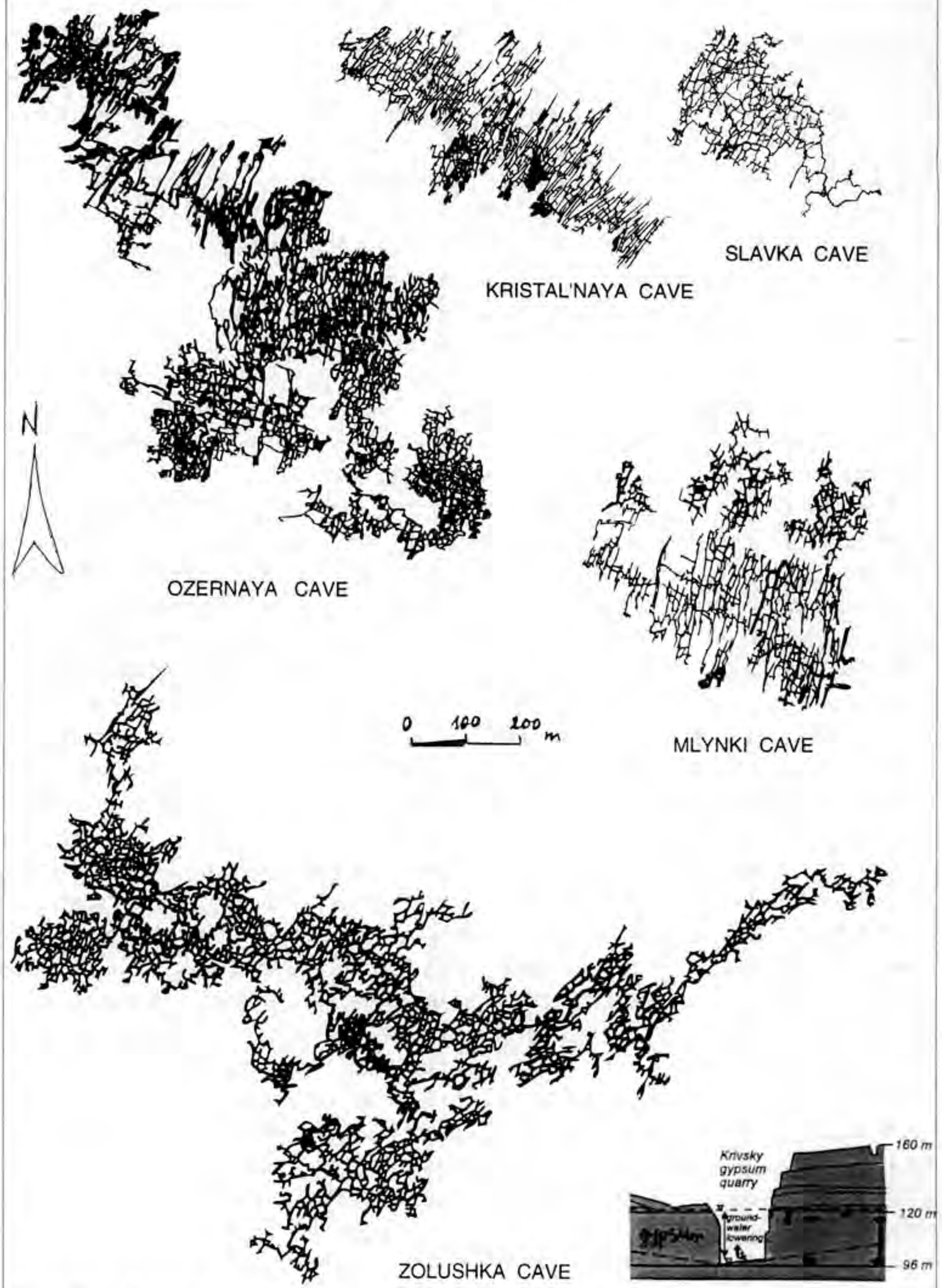

Fig. 3. Maps of some of the major gypsum caves in the Western Ukraine.

values are also characteristic for the fields of Verteba Cave (61%), Bukovinka Cave (57%) and Ozernaya Cave (51%). The average value is of 37%. The coefficient of volume karstification varies from 2-3% (Dzhurinskaja, Mlynki, Slavka and Komsomol'skaya caves) to 12% (Verteba Cave), with an average value of 5%.

3.2. Cave genesis: hydrodynamic pattern and evolution

Recent studies (Klimchouk, 1990, 1992, 1994) suggest that maze caves in this region developed (and are presently still developing in the 3rd zone) under confined conditions, due to effects related to upward cross-formational groundwater circulation between the pre-existing sub-gypsum and supra-gypsum aquifers. Such flow patterns are characteristic of potentiometric low areas, related to topographic lows (valleys) that commonly coincide with zones of enhanced fluid conductivity created within the capping clays by tectonic or stratigraphical discontinuities (Fig.4). Overall discharge from artesian aquifer systems occurs in such areas. Mechanisms of cave system development in such situations are discussed in detail in Chapter I.5, where it is shown that maze patterns will result if appropriate structural conditions exist.

Across the entire studied region, confined hydrogeological settings (with limited discharge and sluggish flow) prevailed during most of the Pliocene, when slow speleogenetic initiation probably occurred. By the late Pliocene to early Pleistocene the old shallow and wide pre-Dniester valley had formed, as evidenced by the extent of the alluvium of 7th and 6th terraces preserved to the north-east of the modern valley. This initial erosional entrenchment into the confining clays created better conditions for discharge, and encouraged establishment of groundwater flow and cross-formational communication within the artesian system. The "great cave belt" of the Podols'ky region lies totally within the limits of this ancient pre-Dniester valley. Its north-eastern boundary approximates to the limits of the old alluvial deposits that are preserved within the modern inter-valley massifs. The two maze caves that lie north of this alluvial limit are related to a separate buried valley that has been traced in that area.

Towards the end of the early Pleistocene and through middle Pleistocene time, active uplifts in the Podol'sky sub-region resulted in further incision of the Dniester, but within a much narrower valley, only slightly wider than the modern one. Also, the left bank tributaries of the Dniester incised rapidly, dividing the area north of the Dniester into large, elongated, sub-parallel massifs. This led to a substantial acceleration of groundwater circulation within the Miocene artesian system and eventual breaching of its artesian confinement; marking a stage of subjacent karst. With further deepening of the surface drainage during late Pleistocene times, conditions of entrenched karst were established, and cave systems in the gypsum became relict.

In the area to the south-south-west of the Dniester valley, overall uplift rates during most of the Pleistocene were much slower, and there was a relative subsidence of some tectonic blocks adjacent to the foredeep. This imposed slow rates of speleogenetic development, which became active only during the late Pleistocene in some of the more uplifted blocks, such as those of Krivsky and Mamalyzhsky that were entrenched by the Prut valley (Zolushka and Bukovinka caves). In the north-western part of the gypsum belt karstification was intensified during the

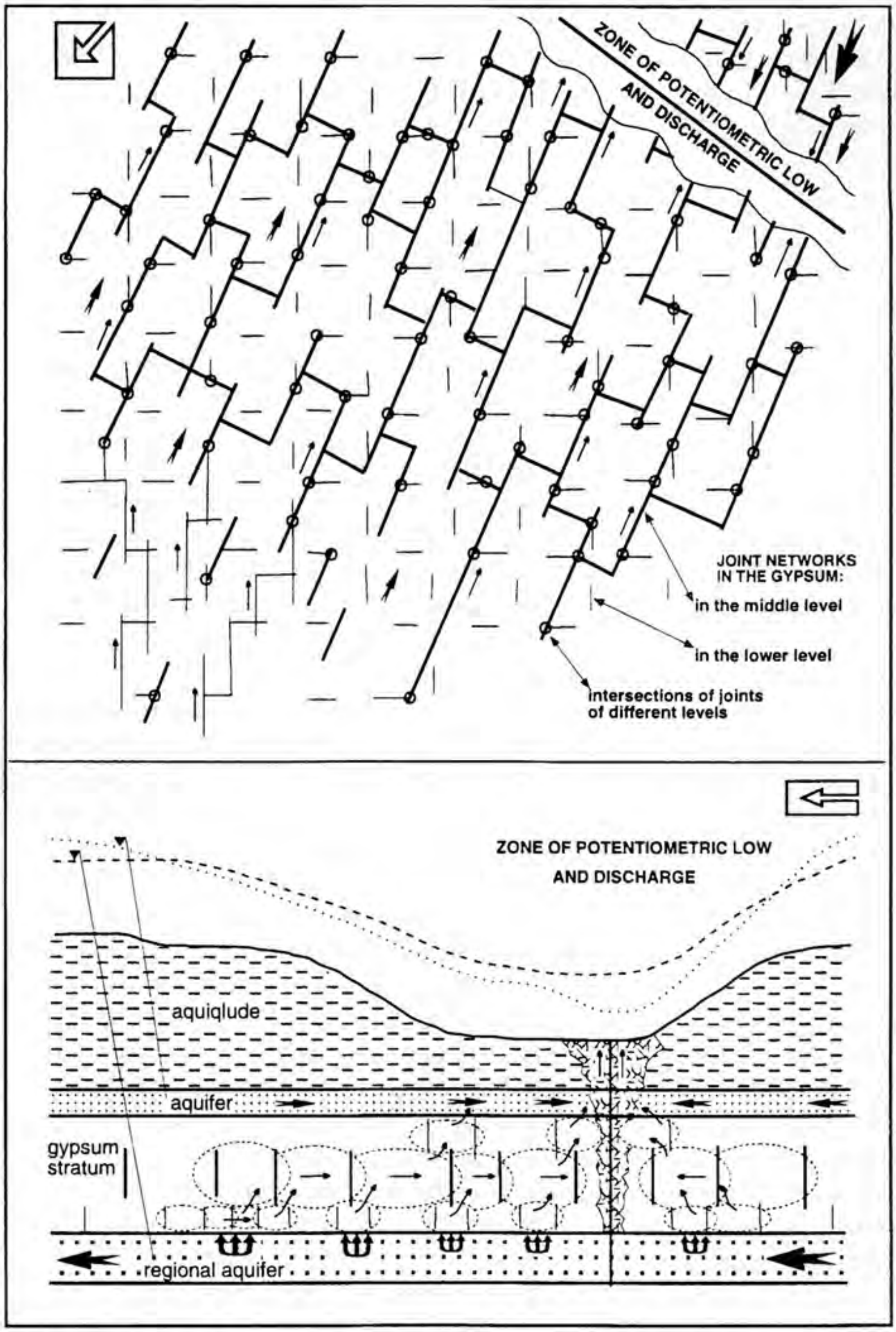

Fig. 4. The initial stage of upward development of multi-storey maze caves under artesian conditions in the Western Ukraine.

middle Pleistocene, being related to valleys that were incised to the top of the Tyrassky Formation but subsequently buried when the local neotectonic movement trend changed from uplift to subsidence. Karst and speleogenetic processes have been reactivated more recently in response to Holocene uplift (which has encompassed the whole region), and also as a reflection of the increasing effect of anthropogenetic impacts (see Chapter I.10).

The hydrodynamic and hydrochemical conditions of cave development during the mature and active stage of artesian speleogenesis can be illustrated by examples from the north-west of the gypsum belt (Jazovsky and Nikolaevsky deposits). Groundwaters entering the gypsum from below (from the sub-gypsum sandy-carbonate aquifer) have a TDS content ranging from 0.4 to 0.6 g L^{-1}, and are very aggressive with respect to gypsum, being able to dissolve it at rates ranging from -2.48 to -25.57mm a^{-1}. Water chemistry and dissolution rates in cavities within the gypsum vary substantially, depending upon the cave system configuration (the actual flow path within the gypsum) and flow velocity. The TDS content ranges from 1.3 to 2.1 g L^{-1}, and dissolution rates range from -0.16 to -3.46 mm a^{-1} (see also Chapter I.3).

Under cross-formational circulation conditions in an artesian system, all available fissures in the gypsum, which hold similar positions within analogous flow paths, will enlarge at comparable rates. This behaviour generally favours the development of maze cave morphologies, but the actual conduit arrangement in any situation will depend upon the initial local fissure pattern.

3.3. Structural prerequisites of speleogenesis

The maze and multi-storey structure of caves in this region is preconditioned, in the prevailing hydrodynamic environment of speleogenesis, by the extent and specific characteristics of the fissure patterns in the gypsum. Vertical fissures are arranged in largely independent networks confined within individual horizons of the gypsiferous unit, each of which is characterized by different rock textures and structures. This feature, together with some topological peculiarities of the fissure patterns, indicates that the fissures are lithogenetic rather than tectonic in origin (Klimchouk, Andrejchouk & Turchinov, 1995; see also Chapter I.1). Fissure patterns at each level have their own characteristic frequency, orientation distribution and degree of lateral connectivity, and elements of these are inherited by the passages that comprise each level of a cave system. This is the fundamental reason for different structures being displayed by passage networks at different levels. The extent and the nature of the vertical connectivity between storeys of fissures (passages) varies substantially between areas (tectonic blocks). The general background of vertical cross-formational groundwater circulation in these artesian systems is that a considerable lateral component of the cave development is caused by 1) the presence of laterally extensive interconnected fissure networks in some horizons and, 2) by the lack of coincidence of permeability structure between the sub-gypsum and supra-gypsum aquifers and between different horizons in the gypsum unit.

All of the caves include some morphological elements within the lower part of the gypsum stratum, which provided upward recharge of developing cave systems from the underlying aquifer. In most cases the fissures in the lowermost horizon do not form extensive laterally connected networks, so that recharge of a continuous network at the next higher storey ("master storey") occurred through the separate fissures of localized small networks (Ozernaja, Slavka, Dzhurinskaja, Zolushka and some areas of Optimisticjeskaja caves). Such "feeder" conduits are commonly numerous and uniformly distributed across an area, providing relatively dispersed inflows of aggressive water to the conduit network of the master storey and supporting uniform dissolutional widening of all passages. In some other cases (such as Atlantida Cave) lateral flow and the development of master passages occurred chiefly along the base of the gypsum unit, with vertical "ascending" domepits and small networks formed locally at the upper storey. In all cases, multi-storey conduit systems developed (with some elements terminated at the base of the overlying sequence), with the ultimate function of conducting groundwater upwards between the sub-gypsum and supra-gypsum aquifers.

3.4. Meso-morphology of caves

The shapes and sizes of the passages, and of the smaller-scale forms produced within the passages, depend upon geological and hydrodynamic factors, the most important of which are the following:

1) shape and size of initial fissures;
2) distinctive structural and textural features of the gypsum within a given horizon;
3) position and function of a given morphological element in a karst circulation system;
4) distinctive features of the local hydrogeological evolution.

Because of the locally varying role of these factors, passage morphology can differ significantly between different parts of a single cave and, especially, between the separate cave levels. Vertical structural/textural differentiation of the gypsum unit (into three distinct sub-horizons across most of the Podol'sky sub-region) is believed to have resulted largely from late diagenetic recrystallization of the rock (Klimchouk, Andrejchuk & Turchinov, 1995). Such differentiation is the main cause of the development of distinct lithogenetic fissure (and, hence, passage) patterns, each confined to a specific horizon. Also, the different functional position of passage levels in cave systems of "ascending" type contribute further to the morphological distinction between levels. Thus, at least the first three of the factors listed above combine to influence the development of different passage morphologies located at different levels.

The reverse situation is even more consistently true: passages developed at the same level within a particular cave area (passages occupying the same geological position, and providing the same hydrological function in a system) are characterized by consistent morphological parameters, as all four of the factors listed above act with uniform weight.

Passages typically have a cleft-like shape, with a flat or gothic-arched ceiling. Also common are relatively wide (2 to 4m) passages with symmetrical horizontal notches and inwardly inclined facets in the walls, or with two or more levels of notching. The ceilings of these passages can also be flat or gothic-arched (see Fig.6 in Chapter I.5). Such morphological features are the result of dissolution driven by natural convection, under either artesian or water table conditions (see Chapter I.5 for details).

Dissolutional cupolas and domepits are widespread, having developed upwards from a master passage for up to 12m above ceiling level. They can be "blind", or open upwards into a passage at the next higher level. Some terminate at the base of the overlying limestone bed. Such domepits may be extended laterally in their upper parts, if a higher level fissure was intercepted. It is likely that cupolas and domepits, as well as another common feature, ceiling half-tubes, are also formed largely by dissolution driven by natural convection,. The development of ceiling half-tubes is achieved by buoyant currents of relatively fresh water that will always tend to occupy the highest available position in a passage containing bulk water that is more highly saturated (see Klimchouk, 1997c, and Chapter I.5 for details). Such half-tubes can commonly be traced continuously from the "feeder" conduits at lower level, through master passages, to domepits that open to the next higher level or reach the upper boundary of the gypsum (see Fig. 5 in Chapter I.5).

During the final stage of artesian speleogenetic development, when the upper confining bed is breached locally by an incising valley or areas of collapse, groundwater flow through a cave system increases dramatically, due to unconstrained discharge. Accelerated growth of the passages along preferred flow paths results in development of the large trunk passages that are recognized in most of the region's caves. In some cases, passages within a particular part of a maze may be enlarged substantially, relative to average passage sizes in adjacent areas. This is exemplified by the Chamber of Chernovtsy Speleologists in Zolushka Cave, where only small pillars remained within a large space that was formed by the coalescing of enormously enlarged passages. Another mechanism responsible for comparatively rapid passage enlargement, which operates more uniformly within specific areas at a particular level, is horizontal notching in response to dissolution at the water table.

Typical features formed under modern entrenched karst conditions are vertical dissolution pipes, which grow due to a focused descending percolation from overlying formations. They are 1 to 3m wide, extend downwards through the full thickness of the gypsum from its top, and are commonly superimposed upon relict artesian passages. Recent linear through caves carrying active streams are relatively rare in the 1st zone but more common in the 2nd zone. Normally they develop along the base of the gypsum, originating from doline ponors and extending towards the nearest entrenched valley. Some such caves may enter areas of relict mazes, where the active streams dissipate and water filters downwards into the underlying aquifer (as is the case in the entrance passage of Optimisticheskaja Cave). Such areas of the caves are prone to short term flooding after heavy rainfall or active snow melting.

3.5. Cave sediments and formations

By far the predominant clastic sediments in the maze caves of the region are successions of fine clays, with minor beds of silty clays (Klimchouk, 1984). These fill passages to a variable extent and can reach 5 to 7m in thickness. The clay material is derived largely from overlying clayey formations and has been intruded into the caves mainly during the later stages of artesian speleogenesis, when breakdown processes became active and flow velocities increased, allowing some redistribution of clastic material. However, gradient fields within the aquifer remained relatively uniform, so that the sediments are very fine grained, exceptionally well sorted and maintain a uniform facies over considerable distances. The number of silty beds increases in the upper parts of the clay sediment sequences, reflecting the more variable hydraulic environment of an unconfined aquifer during the subjacent and early entrenched karst stages. Repeated transitional cycles from a reducing to an oxidizing geochemical environment are marked by the presence of Fe/Mn hydroxide layers (Klimchouk & Rogozhnikov, 1982). Massive deposition of Fe/Mn compounds has occurred in Zolushka Cave, where a rapid transition of the type described has been caused by groundwater abstraction during the last 50 years (Volkov, Andrejchuk & Janchuk, 1987). Sandy-gravel sediments occur in the upper parts of the cave fills, but these are limited to areas that surround active ponors. They have been re-worked and redeposited from the old (late Pliocene to early Pleistocene) alluvial sediments that commonly overlie Sarmatian clays.

Breakdown deposits are also quite common in the caves. They include chip, slab and block breakdown material from the gypsum unit, as well as by material from more massive breakdowns which disrupted the overlying formations. Locally the plastic Sarmatian clays can be injected into caves through breakdown zones, due to the pressure of the overburden. Distribution of breakdown deposits is governed by passage sizes, local textural and structural peculiarities within the gypsum of a given area or horizon, and the presence of tectonic faults.

Various chemical deposits, speleothems and formations are quite common in the gypsum caves of the Western Ukraine (Rogozhnikov, 1984; Turchinov, 1993). Calcite speleothems (stalactites, stalagmites, flowstones and helictites) occur locally in zones of vertical water percolation from overlying formations. Among other carbonate minerals, rhodochrosite occurs within a flowstone in Optimisticheskaja Cave (Turchinov, 1993). Gypsum crystals of different habits, sizes and genesis are the most common cave formations. Those covering the walls in many parts of the caves have a largely subaerial origin, being formed by evaporation of saturated solutions moving as thin films on the walls. Also common are gypsum formations deposited by evaporation of interstitial solutions seeping from the host rock (local covers, and "flowers" of fibrous gypsum). Hoar-frost crystals, "gypsum snow" on passage floors, and gypsum rims are assumed to be precipitated from aerosols (Klimchouk, Nasedkin & Cunningham, 1995). Silicates are represented by lutecite, a variety of cristobalite, found in Optimisticheskaja Cave (Turchinov, 1993). Oxides and hydroxides (Fe/Mn compounds) are common within the clay fill of many caves, or can also occur as covers, stalactites and stalagmites (Zolushka Cave). Manganese minerals are also represented by birnessite and asbolan-buserite in Zolushka Cave (Volkov, Andrejchuk & Janchuk, 1987).

4. Gypsum karst and the origin of native sulphur deposits

Large bio-epigenetic deposits of native sulphur in the pre-Carpathian region are genetically associated with the same gypsiferous unit, and are all located within the 3rd zone described above (see Fig. 1). Sulphur is embedded in epigenetic calcite that partially (at the top) or wholly replaces the gypsum. Views on the origin of these sulphur deposits are quite controversial. Recently (Klimchouk, 1997b) a new interpretation, which implies a fundamental role for gypsum karst in sulphur origin, has been suggested. It is evident that, in general, bio-epigenetic sulphur formation is related to karst, because dissolved sulphates are needed to enable the large-scale sulphate reduction that is a key process within the sulphur cycle. But in the case of the pre-Carpathian sulphur deposits, the role of karst (speleogenesis) as a governor of groundwater circulation in the artesian aquifer system was decisive. The proposed model for the origin of sulphur deposits hinges upon the ascent of groundwater between the sub-gypsum and supra-gypsum aquifers, through karst systems (artesian cave systems) in the gypsum. Such a flow architecture and speleogenetic evolution within the gypsum provided the spatial and temporal framework within which the sulphur cycle processes took place, as well as controlling the geochemical environments, and the migration of reactants and reaction products between them. The model explains the well-accepted relationship of sulphur deposits to buried valleys and karst zones, and resolves many contradictions in earlier interpretation of the geological features of the Tyrassky Formation and the hydrogeological features of sulphur deposits (Klimchouk, 1997b).

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Chapter II.10

GYPSUM KARST OF THE BALTIC REPUBLICS

Bernardas Paukstys & Vytautas Narbutas

Introduction

The Baltic Republics of Estonia, Latvia and Lithuania have karst areas developed in both carbonate and gypsiferous rocks. In the north, within the Republic of Estonia, Ordovician and Silurian limestones and dolomites crop out, or are covered by glacial Quaternary sediments. To the south, in Latvia and Lithuania, gypsum karst is actively developing in evaporites of Late Devonian (Frasnian) age (Fig. 1). Although gypsum and mixed sulphate-carbonate karst only occupy small areas in the Baltic countries, they have important engineering and geo-ecological consequences. Due to the rapid dissolution of gypsum, the evolution of gypsum karst causes not only geological hazards such as subsidence, but it also has a highly adverse effect on groundwater quality.

The karst territory of the Baltic states lies along the western side of the area, called the Great Devonian Field that form part of the Russian Plain (Narbutas, 1960). Within southern Latvia and northern Lithuania there is an area, exceeding 1000 sq. km, where mature gypsum karst occurs at the land surface and in the subsurface. This karst area is referred to here as the Gypsum Karst Region of the Baltic States. Here the surface karst forms include sinkholes, karst shafts, land subsidence, lakes and dolines. In Lithuania the maximum density of sinkholes is 200 per sq. km; in Latvia they reach 138 units per sq. km. Caves, enlarged dissolution voids and cavities are uncommon in both areas.

1. Climate, Geology and Hydrogeology

1.1. Climate

The Gypsum Karst Region is located about 100-200 km south-east of the Baltic Sea. It is characterised by a humid and mild climate, transitional between continental and maritime, these are conditions favourable for karst development. In the region the mean annual precipitation varies significantly from 434 mm to 921 mm, with an average of 640mm. The wettest period is in July and August when 6 to 19 per cent of the annual rainfall occurs. The dryest period is in February when snow accounts for 2.5-6 per cent of the annual precipitation. Evapotranspiration in the karst region removes 75 per cent (469 mm of total precipitation) from the surface (Paukstys & Taminskas, 1992). Favourable conditions for high evaporation are created by shallow groundwater levels and the presence of clays and moraine till which form a vadose zone of low permeability. The total dissolved solids (TDS) in the precipitation amount to 11.3 mg/l, half of which (6.1 mg/l)

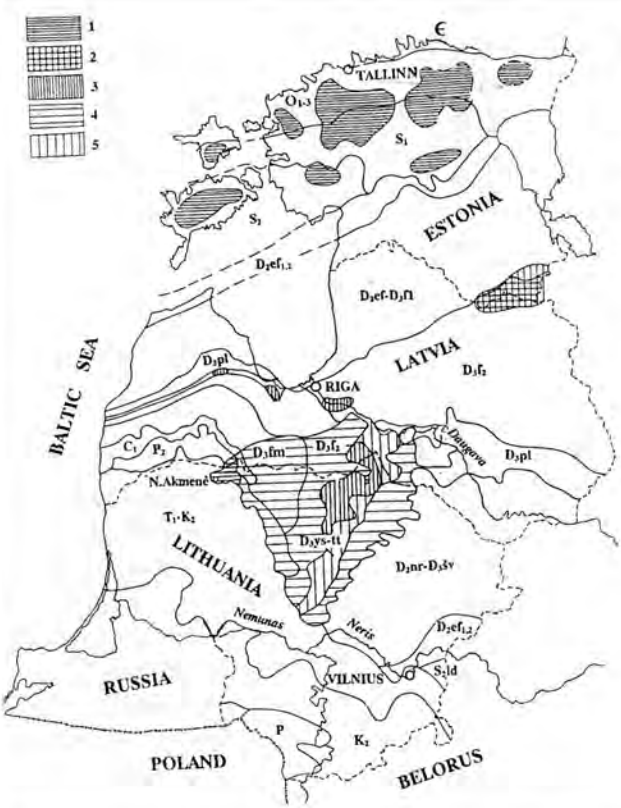

Fig. 1. Karst territories of the Baltic republicks (by V.Narbutas, E.Vodzinskas & U.Heinsalu).
Karst types:
1 = carbonate,
2 = gypsum-carbonate,
3 = active gypsum karst,
4 = old stabilized carbonate karst,
5 = old stabilized gypsum karst.

is composed of calcium and sulphate. This precipitation with a pH of 5.4 is highly aggressive to carbonate rocks, but becomes neutral when it infiltrates the soil and reacts with carbonate there (Paukstys, 1996). Mild winters and humid summers characterise the Gypsum Karst Region. The mean average temperatures range from a low of -5°C in January to a high of +15°C in June.

Surplus humidity and a positive balance of precipitation generate surface run-off and streams that recharge the rivers. The mean annual specific discharge of the karst rivers varies from 4.9 to 5.5 l/sec/km^2, but groundwater contributes only about 5 per cent to this total (Paukstys & Taminskas, 1992).

1.2. Geology

In the Baltic States the karstified gypsum and gypsiferous-dolomitic rocks occur at two stratigraphical levels; the Narva Formation of Middle Devonian age and the Tatula and Salaspils Formations of Late Devonian (Frasnian) age. The gypsum in the Narva Formation occurs at a depth of 100 metres or more and karst features are not visible at the surface. However, buried palaeokarst forms are present and these include breccia-filled pipes and carbonatic debris (Narbutas 1979).

The Late Devonian (Frasnian) gypsum sequences occur within the Tatula Formation in Lithuania and the Salaspils Formation in Latvia. The Tatula Formation includes two gypsum layers, the lower one is called the Pasvalys (20m thick) and the upper one the Nemunelis (15m thick). The gypsiferous rocks are underlain by the dolomites and marls of the Pliavinias Formation which in turn are underlain by the thin (2-9m) Jara clays and marls. Below this clay thick sandstones and argillaceous sandstones of the Sventoji and Upninkai Formations occur forming a major aquifer. This aquifer overlies the Narva clay Formation that is the regional aquiclude present at the base of the gypsum karst region. The Late Devonian gypsiferous rocks dip at between 10-15' and 2o to the west. The sequence has been planed off by glacial action and the gypsum crops out as a narrow southwest-trending strip between 12 and 20 km wide (Narbutas, 1979). This strip is mainly covered by thin Quaternary deposits; within this zone modern karst with sinkholes and subsurface cavities is highly developed (Fig.1).

1.3. Hydrogeology

Hydrogeologically, the Gypsum Karst Region forms part of the Baltic Artesian Basin and is located in a zone of active water circulation. Both the Devonian and Quaternary formations are water-bearing and form a single interconnected hydraulic system of aquifers. All the aquifers are being exploited to varying degrees for domestic and industrial use. The Quaternary glacial sands contain mainly fresh calcium bicarbonate water (TDS 0.5 - 0.8 g/l) which is often heavily polluted by nitrogen and organic compounds. The karst aquifer typically has slightly mineralised, but very hard water (TDS 1.5 - 2.4g/l; total hardness up to 35 meq/l). Calcium and sulphate are the main chemical constituents of this water. The aquifer is very vulnerable to pollution and as a result the level of contaminants (nitrogen and organics) often exceeds the maximum allowable concentration for drinking water (Klimas & Paukstys, 1993).

The dolomite aquifer below the gypsum karst rocks usually contains fresh calcium-magnesium bicarbonate water (TDS 0.5 - 0.8g/l; total hardness up to 10meq/l). However, in places due to hydraulic connection with the overlying mineralised karst water, calcium sulphate water (TDS of 1-2g/l) is locally present; some observation wells are also showing traces of pollution.

The lowest aquifer is composed of Middle Devonian sandstones with groundwater of high quality (TDS 0.2 - 0.6g/l; total hardness 5-7meq/l). However, sulphate concentrations locally reach 100mg/l and traces of nitrogen compounds show that this aquifer is locally connected to the upper water-bearing horizons (Paukstys 1996).

2. Karst Forms

Within the active gypsum karst region of Lithuania 8500 sinkholes were counted in an area of 400 km^2. The majority of sinkholes (about 60 per cent) are of oval shape, with the diameters of 10-50 m. The depth of the sinkholes varies from 2 to 12 m, the average being 5 m (Buceviciutë & Marcinkevicius, 1992). The sinkholes are concentrated along the valleys of Mûsa, Levuo, Pyvesa rivers and also along the water divides of these rivers. The density of sinkholes in such areas exceeds 20 per square kilometre; the highest density of sinkholes (200 per km^2) was recorded in the Karajimiskis geological reserve (Paukstys, 1996).

In Latvia the average density of karst forms in the vicinity of Skaistkalne village is 13 sinkholes per square kilometre, but the highest concentration is 138 per square kilometre. The densities of sinkholes in other parts of Latvia are: Baldone and Adazi -5 sinkholes/km^2, Kemeri-4 sinkholes/km^2, Saulkalne -2 sinkholes/km^2. Sinkholes and collapses were also observed in the vicinity of Riga city, but because they are all now filled with soil their density is not known. In Latvia the some of the sinkholes exceeds 50m in diameter and 10m in depth. Some of the large collapses are of complicated shape with several ponors; they form systems of interconnected holes in the land surface.

In the Gypsum Karst Region, the majority of the collapses are small to medium in size with diameters ranging from 1-2 to 10-15 and depths from 1 to 6 m. Most of holes are dry, but some of them are periodically filled with water. The deeper sinkholes reach unconfined groundwater and sometimes the level of the confined, artesian water; in such cases springs occur, especially along the river valleys. In Lithuania, karst springs occur in the valleys of Levuo river at Pasvalys, next to the Orija river near Berklainiai village and the Apascia river at Draseikiai village. In Latvia karst springs occur along the Iecava and Memele rivers. Some springs are the sources for rivers; the spring that discharges from a shallow sinkhole, with a diameter of 13 m in Likenai village, creates the Smardone stream, a tributary of the Tatula river. Conversely, the 8 km long Pozemis stream disappears underground in a karst fracture. Both in Lithuania and Latvia, some of the large collapses are water filled and form small lakes, some over 10 m deep. Lake Ilgasis ("Long Lake" in Lithuanian) at Kirkilai village is composed of 30 amalgamated sinkholes; it is 1100 m long and 200 m wide (Kilkus 1977). In the Gypsum Karst Region the lakes have mixed recharge both from the precipitation and from the groundwater that commonly gives their water a slight smell of hydrogen sulphide.

Surface karst forms are common, but only one gypsum karst cave is known today in Lithuania. This cave, at the Karajimiskis Geological Reserve was given the status of a geological monument. The cave entrance is at the bottom of a karst hole 9.5 meters deep. The cave comprises of a main cavity, which is partly filled with water and three narrow passages. The height of the main cave is 3.1 m and the total length of the passages is 46 m. The total area of the cave is 42 square metres, with a volume of 28 cubic metres (Laiconas, 1979). The walls and sides of the cave are covered with water-eroded scallops and it is clearly of phreatic origin. However, the cave is now only about half full of water and a solution roof or laugdecke is present just above the summer water level. The cave water is of calcium sulphate type (TDS 1.5-2.2 g/l; total hardness 23-29 meq/l). The groundwater temperature in the cave does not exceed +5°C even in mid summer.

3. Environmental Problems Associated with Gypsum Karst

The main human activities influencing gypsum karst development are groundwater abstraction and agriculture.

The interconnected system of aquifers, both in and around the Gypsum Karst Region, is being exploited for drinking water supplies by dug and drilled wells. Besides the individual wells, two waterworks in the towns of Birzai and Pasvalys respectively abstract 2000 and 2600 m^3/day of groundwater. As a result of these abstractions, the water level at the Pasvalys waterworks has fallen by 7.5m since 1970. At Birzai the drawdown has been 8m since 1961. Groundwater abstraction boosts gypsum solubility, it also accelerates the removal of dolomite debris from subsurface cavities so that it can be redeposited into other openings or removed by pumping (Paukstys, 1996).

Agriculture also has a strong regional influence on karst development and protection. In common with other parts of Lithuania and Latvia farming is highly developed in the Gypsum Karst Region. The shallow unconfined waters in many of the domestic wells of the region and the karst aquifer are both heavily polluted by nitrogen and organic compounds (Paukstys, 1996).

Resulting from the investigations of the natural and human-induced factors contributing to karst development, a series of protection measures for the Gypsum Karst Region were instigated.

In Lithuania the karst area was divided into two parts; a karst protection zone of 166,000 ha and a zone of active karst development with an area of 27,600 ha. (Paukstys, 1996; Narbutas 1994). Considering the number of sinkholes present per 100 ha, which indicates the vulnerability of the karst terrain, the active karst zone was further subdivided into four land groups. Each land group has a specific level of agricultural restriction imposed upon it, these are:

Land group 1 (up to 20 sinkholes/100 ha) - grain crops should compose at least 50% of arable lands, perennial grass 40% and root crops (potatoes and sugar beet) not more than 10%. Fertilisers are limited to a maximum of 90 kg/ha of nitrogen-potassium-phosphorus (NPtP- active ingredients) and 80 t/ha of manure. Triazinic herbicides and chloroganic insecticides are prohibited.

Land group 2 (20/50 sinkholes/100 ha) - grain crops should compose 43% or arable lands and perennial grass 57%. Root crops (potatoes and sugar beet) are prohibited as are the setting up of new orchards and gardens. Fertilisers are limited to a maximum of 60 kg/ha of NPtP and 60 t/ha of manure.

Land group 3 (50 - 80 sinkholes/100 ha) - Perennial grass and pastures only are allowed. Fertilisers are limited to a maximum of 60kg/ha NPtP. Mineral nitrogen fertilisers are prohibited as are pesticides (except for fungicides).

Land group 4 (80 - 100 sinkholes/100 ha) - only meadows and forests are allowed. All fertilisers and pesticides are prohibited. In all the land groups a 25m radius protection zone is required around each doline. Within this protection zone only grass without fertilisers or pesticides may be grown.

Ecologically sound agricultural plans have been designed for each land group. Thus in Lithuania, the protection of karst water from pollution, and the reduction of human impact on the vulnerable karst area, is now official Government policy. Groundwater abstraction is only allowed from the sandstone aquifer, underlying the karstic one. The planned mining of the Skaistkalne gypsum deposit in Latvia and Rinkunai deposit near Pasvalys (Lithuania) were both cancelled for environmental reasons; these were to avoid dewatering, to protect the water quality and to prevent subsidence.

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Chapter II.11

GYPSUM KARST OF THE PRE-URAL REGION, RUSSIA

Vjacheslav Andrejchuk

1. General characteristics

Gypsum karst is a widespread phenomenon in the Ural region, predominantly along its western periphery. Sulphate rocks belong to various evaporitic formations deposited during different epochs of the Palaeozoic, from the Silurian to Permian. They occur within the sedimentary cover within a few hundred metres of the surface throughout a vast area, stretching from the arctic Novaja Zemlja Islands to the hot deserts of the pre-Caspian region. In tectonic terms, their extent corresponds to the western flank of the Eastern-European Platform and the adjacent Ural Foredeep.

Silurian, Devonian and Carboniferous sulphate rocks are overlain everywhere in the region by a thick cover of Permian deposits, that also contains abundant sulphate. The latter are commonly close to the surface and display well developed karst features. However, the areas where gypsum karst is found at the surface are small, relative to the area where sulphates are present within the upper few hundred metres of the geological sequence.

The largest areas of shallow gypsum occurrence (and hence of prominent karst features) lie within the Middle Pre-Urals (Fig.1), where the gypsiferous rocks form two areas of different size: a western area (within the platform flank) and an eastern area (within the foredeep). The tectonic and stratigraphical positions of gypsiferous sequences are shown in Fig.2 (which corresponds to the line A-B on Fig.1-C). The sulphate rocks of the Middle Pre-Urals are Early Permian (Kungurian) in age. The Kungurian Formation consists mainly of evaporites, and within it the Irensky Member is composed entirely of gypsum intercalated with carbonates (Fig.3). Karst processes proceed most intensely at depths of 150-180m. In many places the upper part of the gypsiferous sequence has been destroyed by karstification, leaving characteristic karst breccias.

The settings of gypsum karst development depend mainly upon the depth of surface erosional entrenchment into the sulphate sequence. In most of the area river valleys incise quite deeply, but their floors remain within the sequence. Locally rivers incise down to the underlying carbonates of the Artinsky Formation. Such settings determine particular features of the hydrodynamics, including the presence of vadose and phreatic zones, the type of active groundwater circulation, the extent of recharge from the surface on inter-valley massifs and the degree of discharge along the river valleys.

Regional trends of gypsum karst development are related to the occurrence of sulphates on both sides of the Ufimsky Swell and to the hydraulic connections between karst groundwaters within carbonate rocks in the axial area of the structure and those within sulphates at the sides (see Fig.2). The axial area (locally known as the Ufimsky Plateau), is higher, and physically separates the two areas of sulphates. It is an extensive recharge area, while the western and eastern slo-

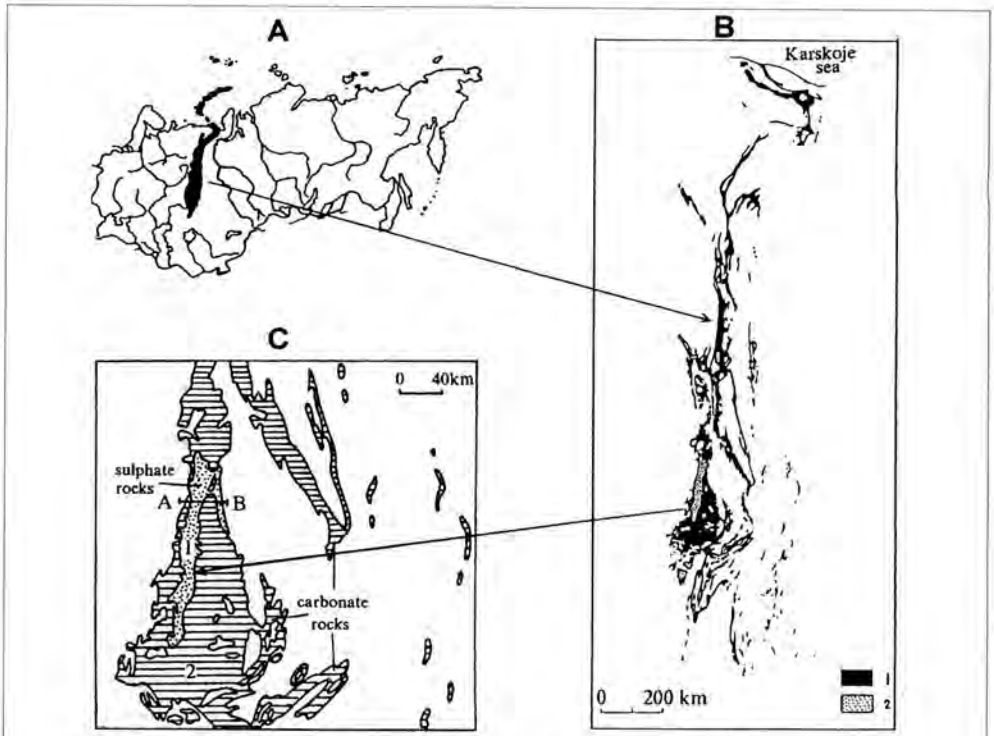

Fig.1. Location of gypsum karst areas in the Middle Pre-Urals: A = Urals on the map of the former USSR; B = distribution of carbonate (1) and sulphate rock in the Urals region; C = gypsum karst areas in the Middle Pre-Urals.

pes of the structure are essentially discharge zones (Fig.4). On the western slope large karst springs commonly lie along the contact between sulphate and carbonate rocks, while on the eastern slope the whole of a narrow, elongated area of sulphates along the contact with the carbonate rocks is the discharge zone for groundwaters from the Ufimsky Plateau. Springs are commonly of upwelling type.

The western area of gypsum karst in this region stretches from north to south for almost 200km, with a width between 20-40km. Most of the area is drained via the valleys of the Sylva and Iren' rivers, which entrench into the sulphates to depths of 30-90m locally. The thickness of the sulphate sequence reaches 100-150m, and it is covered by 0-50m of eluvial and karst-breakdown deposits. Inter-valley massifs comprise relatively flat and slightly hilly plateaux, with patterns of dry valleys and dolines. The thick cover of loose sediments allows thick soils to form, although the stage of drainage development and surface run-off locally determines the dryness of the land. This influences the formation of stepp and stepp-forest landscapes whereas, according to general climatic zonation considerations, there should be southern taiga and mixed forest landscapes in this area, as represented in adjacent non-karstified areas.

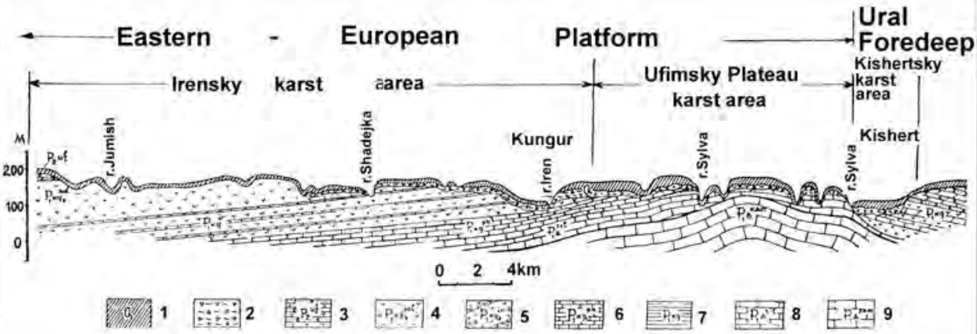

Fig.2 Geological section of the Ufimsky Swell at the latitude of Kungur city (After V.S.Lukin). 1= alluvial and fluvioglacial terrace deposits; 2 = karst-collapse deposits; 3, 5, 7 = terrigenous rocks of different ages; 4 = sulphate rocks (gypsum and anhydrite with limestone beds); 6 = carbonate rocks (limestone, dolomite); 8 = reef limestone; 9 = silicified limestone.

Water tables within the karst aquifers lie at depths of 30-80m, depending upon local relief. The discharges of the karst springs are commonly within 1-40 L/s, some reaching 100 L/s and more. Karst waters have an SO_4-Ca composition and TDS contents between 2 to 3 g/L.

The superficial karst morphology is quite varied. On the rocky outcrops of the rivers Iren', Asla and Sudinka, rillenkarren develop. On the inter-valley massif between the Asla and Sudinka rivers there are fissure-like and cylindrical pits up to 20m deep. However, dolines are the most typical landforms. Their diameters normally range between 5-30m, but locally reach 50-100m or more. Depths commonly lie within the range 1-2 to 10-15m. Doline density varies between 50-250 units per km^2. The highest densities are recorded in zones aligned along the valleys, and numbers decrease towards the watersheds, according to the increase in overburden thickness. Dolines commonly form fields, or are aligned along tectonic lines. Fluviokarstic ravines, also characteristic for the area, are drained by large dolines.

Some 150 caves in gypsum have been explored within the western area, the longest being Kungurskaja (5600m), Zujatskaja (1410m), Nizhnemikhajlovskaja (1400m), Kichmenskaja Ledjanaja (470m) and Bol'shaja Mechkinskaja (350m).

The eastern area corresponds to the narrow junction belt between the Eastern-European Plain and the Ural Foredeep (see Fig.2). The sulphate rocks dip toward the foredeep where they are replaced by terrigenous sediments. The whole area is a discharge zone for karst groundwaters from the Ufimsky Plateau (Fig.4). Deep water discharges as surface springs, and also passes into alluvium and karst breccias. When passing into the sulphates, fresh HCO_3-Ca waters derived from the adjacent carbonates acquire an SO_4-Ca composition and their TDS content increases to 2.6-3.0 g/L. The total spring discharge in this relatively small area exceeds $2m^3/s$.

Superficial karst forms are quite varied and include dolines, karst valleys and lakes. Karst depressions are also quite typical of the area. They reach 1-2km in lateral dimensions and are loca-

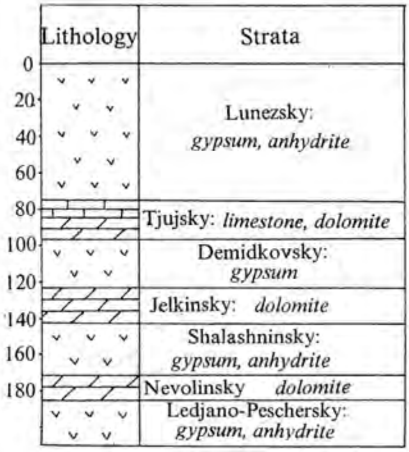

Fig.3. Divisions of the Irensky Member of the Kungurian Formation (After Gorbunova et al, 1992).

ted along the contact between carbonates and sulphates in areas of focused discharge of the karst groundwaters. There are some large upwelling karst springs and lakes at the bottoms of the depressions, which give rise to small rivers that connect adjacent depressions, producing elongated karst-erosional valleys (Fig. 5). These depressions resemble poljes in terms of size, morphology and hydrology. The largest depressions are Nizkovskaja, Dreminskaja, Burtzevskaja, Masuevskaja and Suksunsko-Sovetinskaja.

Within the eastern area seven relatively small caves have been explored. The longest is Varsanofjeva Cave (200m), located in the Masuevsky depression. Its entrance is located at the foot of the collapse called Volchja Jama (Volf's Pit), which is 50m deep and 100m in diameter.

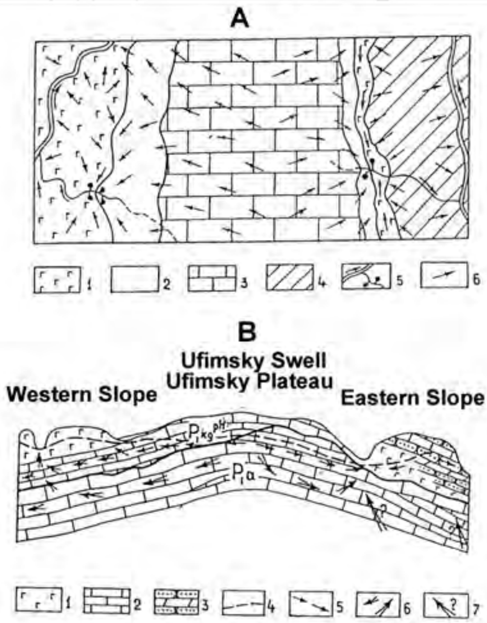

Fig. 4. The general scheme of groundwater circulation within the Ufimsky Plateau (After Turyshev, 1962). A = plan: 1 = sulphate rocks of the western and eastern slopes of the Ufimsky Plateau; 2 = karst-breakdown deposits, karst breccias; 3 = carbonate rocks; 4 = terrigenous rocks of the Urals Foredeep; 5 = river courses and karst springs; 6 = directions of groundwater flow. B = profile: 1 = sulphate rocks; 2 = carbonate rocks; 3 = terrigenous rocks; 4 = potentiometric surface of groundwaters; 5, 6, 7 = directions of groundwater flow.

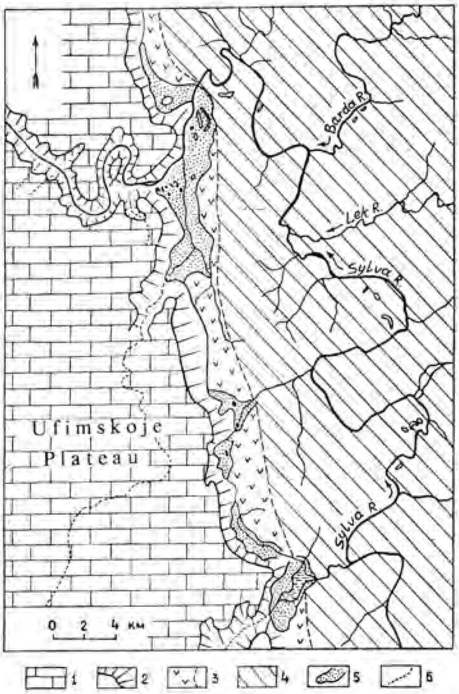

Fig. 5. The area of sulphate rocks with karst depressions on the contact between carbonate rocks of the Ufimsky Plateau and terrigenous rocks of the Ural Foredeep. 1 = carbonate rocks, 2 = slopes of the Ufimsky Plateau, 3 = terrigenous rocks, 4 = karst (fluviokarst) depressions with large springs in their floors, 6 = dry valleys.

The gypsum karst of the Middle Pre-Urals is remarkable in many respects. Below only some aspects specific to the region are briefly outlined.

2. The fissure structure of sulphate rocks and karstification

The sulphate rocks of the Pre-Urals, have experienced several cycles of uplift-subsidence, gypsum-anhydrite-gypsum conversions, and re-crystallisation during Mesozoic and Cainozoic times. This, along with other factors such as the stratification of the sequences, determines the distribution within them of zones of enhanced fissuring. Not only tectonic, but also lithogenetic, bedding and unloading fissures are well-developed. For this reason fissure permeability tends to be rather homogenous and isotropic. Such structural conditions have played an important role in determining particular features of speleogenesis. The high density of partings favours rapid saturation of the circulating waters and prevents development of substantial caves below the zone of active circulation. Large caves, such as the Kungurskaja Cave, are located within the zone of water table fluctuations and lateral groundwater circulation. Caves in the region are characterised by comparatively small dimensions and an abundance of breakdown, which complicates speleological investigations. The type of fissuring described above is the main reason that large maze caves, like those developed in the relatively more massive gypsum, with distinct fissuring, in the Western Ukraine, are not formed in the Pre-Urals.

3. Morphogenesis of river valleys

Valleys of relatively large rivers (Sylva, Iren', Babka) change their morphology sharply when they enter the gypsum karst areas. Whatever the shapes of the valleys outside these limits (whether symmetrical-terraced, V-shaped or canyon-like), within the gypsum karst areas they become wide and assume a trough shape. Valley floors (lower terraces) reach 0.5 to 3km in width, while outside the limits of the gypsum karst areas their widths do not exceed 0.1km. River beds take on a meandering form, and old meanders are abandoned, leaving ox-bow ("mort") lakes. The valley sides are steep, and one side tends to be cliff-like, 50-90m high, displaying rocky outcrops with numerous fissures and caves. The trough-like valley morphology influences the hydrological regime of the rivers. It reduces high flow rises in water level elevation, as water is able to flood across a wide valley floor and backflood into internal parts of the karstified massifs, where water tables are a few meters lower during such periods. The step-sided shapes and the widening of valleys within the gypsum areas can be explained by the effects of active dissolution and erosion at the bases of gypsum outcrops and by rapid wall retreat due to breakdown, followed by dissolution of gypsum clasts by river water.

4. Speleogenesis

Caves in the gypsum karst of the Pre-Urals were formed in different settings. The most extensive caves (Kungurskaja, Novomikhajlovskaja and others) developed in the near-valley parts of the massifs, in the zone of water table fluctuations related to backflood intrusion of fresh river water. This view is supported by the shapes of passage cross-sections, which display horizontal notching (Fig.6). Studies have shown (Lukin, 1967, Andrejchuk, 1992) that such polygonal cross-sections form due to notching at the water table caused by hydrochemical stratification of water in cave lakes, and due to the localised protective action of fine-grained sedimentary cover deposited on inwardly inclined facets (1).

Flat ceilings in polygonal cross-section passages have formed due to water table fluctuations. When the water table rises, water dissolves pendants and protrusions, creating flat surfaces that can be traced throughout extensive areas.

Polygonal cross-sections, which are so typical of the caves in this region, represent a combination of flat ceilings and inclined walls. The process of their formation, and the complication superimposed on the background by the gradual lowering of average and high-flow river water and water table levels, are shown schematically in Fig. 6. In large caves that develop during prolonged periods, the passage cross-sections acquire complex shapes, with numerous wall notches and flat surfaces at various ceiling levels. Thus, polygonal cross-sections appear to provide strong evidence of cave development within the water table zone.

(1) See chapters I.5 and II.6 for an alternative explanation of facets and flat ceilings, which involves natural convection effects (Editor's note).

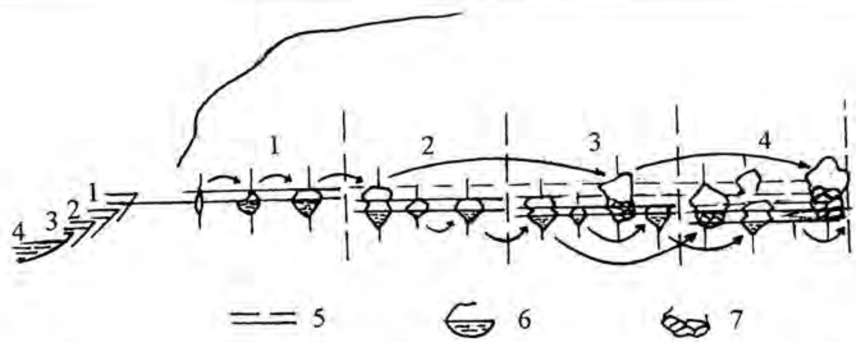

Fig. 6. Development of polygonal cave passage cross-sections in a gypsum massif entrenched by a river valley.

5. The evolution of sulphate karst

The sulphate karst of the Pre-Urals has been developing under continental conditions since Mesozoic times. During this period repeated cycles of uplift and subsidence have occurred. This cyclicity has resulted in the presence of over-deepened valleys (up to 60m) that have subsequently been filled with Neogene sediments, karstified horizons that occur well below the recent erosional base level (2), lithified karst breccias, and numerous areas of breakdown.

A significant feature that results from this prolonged sulphate karst evolution is the presence of various sedimentary and residual rock accumulations. Locally, within the intervalley massifs and in old karst depressions, white and coloured Neogene clays, and quartz sands and gravels occur. Everywhere the sulphate rocks are covered by clayey-carbonate deposits (5-50m, and locally more, in thickness), representing the residual material produced during disintegration of the upper parts of the sulphate succession. These deposits are composed by residual clays and clasts of dolomite and limestone that were originally interbeds within the sulphates and have been broken in the course of cavity development. The thickness of such cover is greatest within the Ufimsky Plateau (see Fig.2) where, during the Mesozoic and Cenozoic, the sulphate sequence was wholly disintegrated due to the effects of the most active uplifts. The disintegration process is illustrated in Fig. 7.

(2) Such horizons can also be a result of recent intrastratal karstification; see Chapter I.4 (Editor's note).

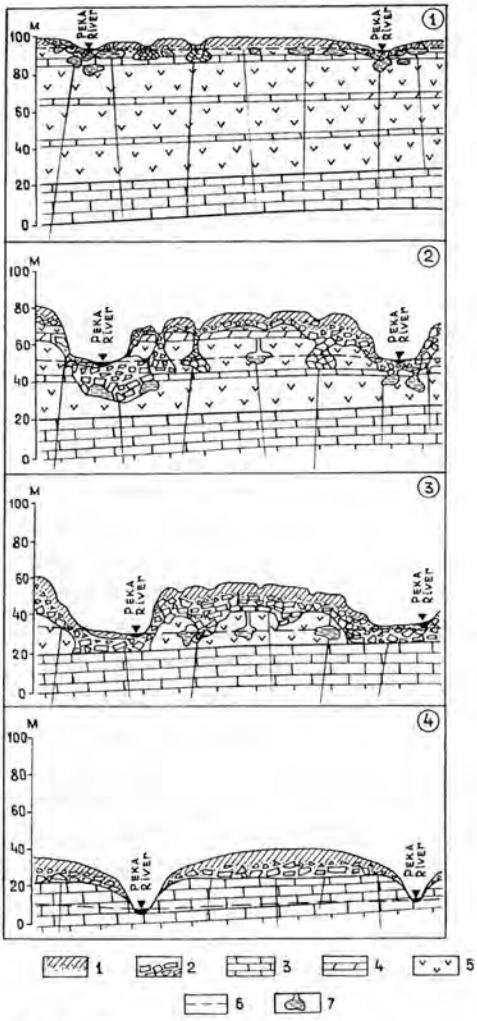

Fig. 7. Karstic disintegration of sulphate rocks within an intervalley massif.
1 = loose eluvial sediments (clays, loams),
2 = karst breakdown deposits,
3 = limestone,
4 = dolomite,
5 = sulphate rocks,
6 = groundwater level,
7 = underground cavities.

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Chapter II.12

GYPSUM KARST IN THE SOUTH OF THE SIBERIAN PLATFORM, RUSSIA

Yury Trzcinski

Carbonate, sulphate and salt deposits in the sedimentary rocks of the Siberian platform support extensive karst development that encompasses about 25% of the study region. Karst is associated with carbonate, gypsiferous and salt formations of Cambrian, Ordovician, Silurian and Devonian age. Sulphate karst is developed particularly extensively in the south of Priangarie (the Angara region), where the valley of the Angara river stretches across a 70 to 100km-wide zone of gypsiferous formations. The area comprises a high plateau, with main streams entrenched by as much as 200m.

The geology of the southern part of the Priangarie region is characterized by the occurrence of Lower and Upper Cambrian sedimentary rocks, as well as overlying lacustrine/continental deposits of Jurassic age. Among the Lower Cambrian deposits, only rocks belonging to its upper units (the Angara and Litvintsev members) crop out within the area. The Angara Member is composed mainly of different kinds of dolomite and dolomitized limestone, which are silicified at some levels, or contain numerous siliceous mottlings. More rarely the dolomitic rocks include intercalations of marl, limestone and quartzose sandstone. The rocks of the Angara Member are overlain conformably by the Litvintsev Member, which belongs to the upper part of the Lower Cambrian and the lower part of the Middle Cambrian. The Litvintsev Member is composed of grey, fine-grained, laminated dolomites and, to a lesser extent, massive and thickly bedded dolomites with numerous stylolitic partings. In the upper part of the unit thick beds (30 to 40m) of anhydrite and gypsum, as well as of gypsiferous dolomites, are common. The lower slopes of the Angara and Zalarinka river valleys, and slopes of numerous ravines, are cut within these rocks, and the beds are intensely karstified.

In the Shalotsky area the typical succession includes gypsiferous rocks and has the following pattern. A 10 to 12m-thick bed of dense, highly fissured and cavernous dolomite, overlies a gypsum-anhydrite sequence with dolomite intercalations. At a depth of 30 to 35m within this gypsiferous sequence is a 6m-thick layer of gypsiferous dolomites, with some minor gypsum intercalations. The massive fine-grained dolomites are underlain by the gypsum-anhydrite rocks. Dissolution features are abundant along the contact of the sulphate rocks with the dolomites, generally being represented by karst cavities that have been filled with clayey material or dolomite powder. Open cavities along the upper contact of the karstified rocks are rare.

Vologodsky (1965, 1975) distinguished three stages of karst development in this region, and these occurred during the Mid Cambrian, in pre-Jurassic times and during the Quaternary.

Evidence of Mid Cambrian karstification is found only in the Oka river basin. Here there are relict sinkholes buried beneath rocks belonging to the Upper Cambrian sequence, there are ancient carbonate breccias and there is a local reduction in the thickness of the beds that comprise the upper part of the Angara Member.

There is more abundant evidence of pre-Jurassic karstification in the region. This karst episode produced substantially more destructive effects than those related to more recent karstification. The pre-Jurassic karst development occurred predominantly in the south of the region, where Upper Cambrian deposits were removed by erosion long before the Jurassic. This stage is distinguished by the presence of extensive fields of kaolin-filled sinkholes and of regionally widespread breccias and brecciated dolomite beds, as well as by the effects of rock silicification in the upper parts of the Angara Member. Leaching of enormous quantities of sulphate and carbonate from the upper parts of the Angara Member caused thick horizons of dolomite to be converted to carbonate breccias. This resulted in substantial differences in the nature of the Angara Member as preserved in the northern and southern areas, both in terms of lithology and thickness. In the southern area gypsiferous rocks are poorly represented, having been largely dissolved during pre-Jurassic times, whereas they remain abundant and widespread in the north. Also in the southern area brecciated dolomites correspond stratigraphically to beds that were originally gypsiferous, with thicknesses 2 to 3 times less than those of the original sulphates. Substantial localized reductions in the thickness of the Angara Member (changes of to 50 to 100m thickness within 2 to 3km of outcrop) suggest that the karstification had a great and dominantly destructive effect.

A gypsum karst of Quaternary age is developed widely in the valleys of the rivers Angara, Oka and Belaja and their tributaries. At present practically the whole thickness the Angara Member has been subjected to karstification, with the effects being most intense in the upper part of the sequence.

The solute load of runoff from the gypsiferous rock areas is estimated at 170 t/km^2. Chemical denudation rates vary from 0.02 to 0.08mm/year. The overall surface lowering rate in geologically recent times is estimated roughly at 1m per 10 to 12 thousand years. Cumulative amounts of karst denudation of sulphate and sulphate/carbonate formations during the Quaternary are estimated to be approximately 70 to 80m and 20 to 30m respectively.

Morphologically, gypsum karst is typified by sinkholes, caverns, blind valleys, karst trenches and dissolution troughs (Pulina & Trzcinski, 1996). The superficial forms are represented mainly by sinkholes of corrosional and suffosional origin. Most old sinkholes are in the range 20 to 80m in diameter (rarely 100 to 120m) and 8 to 20m in depth. Groups of sinkholes that have fused together commonly form 150 to 200m-long depressions. Recent collapses are pit-like or pitcher-like in shape (immediately after their formation and before secondary modification). The maximum recorded sinkhole depth is 38m, although depths decrease rapidly with time due to in-washing of fill materials. Large sinkholes are confined to zones that are related to tectonic faults, particularly to areas where these cross each other. In some areas of well-developed gypsum karst in the Priangarie region the density of sinkholes reaches 200 to 250 units per km^2.

Caves are commonly located in distinct zones along the valley slopes. The largest caves are Balaganskaja and Khudugunskaja. These large caves, as well as the smaller ones (commonly 20 to 50m in length), were formed within zones of horizontal groundwater circulation, and a multi-level structure is common, reflecting changes of base level.

Intense economic development in East Siberia during recent years has had substantial impact on the karst. In particular, activation (or re-activation) of karst processes has been induced by the creation of artificial reservoirs. For example, the growth of the Bratsky reservoir has led to dramatic changes to natural conditions along its shore areas (Problems of Protection..., 1993; Trzhtsinsky & Filippov, 1981). These changes have imposed accelerated rates of karst deformation, including the development of collapse sinkholes and subsidence trenches. Many of these have caused damage to buildings and constructions. Some shore zone areas have become unsuitable for industrial and even for agricultural use.

The intensification of gypsum karstification that followed construction of the Bratsky reservoir resulted in the development of new sinkholes and pits up to 40m deep, with volumes up to 7,000m^3. Formation of sizable sinkholes, a typical effect during the early period of the reservoir's existence, was due to rejuvenation of palaeokarstic features. Sinkhole development in later years has been caused mainly by water table fluctuations induced by water level changes in the reservoir. Since the time of the initial impounding, the gypsum karst activity has not diminished, but has tended to expand its area of influence. The zone of sulphate karst activation induced by construction of the reservoir is now 6km wide. The maximum rate of appearance of new collapses occurs within a 0.5 to 1.0km-wide zone along the shore, where it ranges between 0.8 to 10.0 units per km^2 per year.

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Chapter II.13

GYPSUM KARST IN CHINA

Lu Yaoru & Anthony H.Cooper

Abstract

The People's Republic of China has the largest gypsum resources in the world and a long history of their exploitation. The gypsum deposits range in age from Pre-Cambrian to Quaternary and their genesis includes marine, lacustrine, thermal (volcanic and metasomatic), metamorphic and secondary deposits. The gypsum is commonly associated with other soluble rocks such as carbonates and salt. These geological conditions, regional climate differences and tectonic setting strongly influence the karstification process resulting in several karst types in China. Well developed gypsum palaeokarst and some modern gypsum karst is present in the Fengfeng Formation (Ordovician) gypsum of the Shanxi and Hebei Provinces. Collapse columns filled with breccia emanate upwards from this karst and affect the overlying coalfields causing difficult and hazardous mining conditions. Gypsum karst is also recorded in the middle Cambrian strata of Guizhou Province and the Triassic strata of Guizhou and Sichuan Provinces. Gypsum-salt lake karst has developed in the Pleistocent to Recent enclosed basin deposits within the Qinghai-Xizang (Tibet) Plateau.

Introduction

Gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$) are important industrial minerals in The People's Republic of China which has the world's largest reserves and second largest annual production (Chinese Institute of Geology and Mineral Resources, 1993). The rapid dissolution of gypsum causes karst to develop quickly (Lu Yaoru et al., 1966) and commonly results in geological hazards such as collapse, land subsidence and degraded and polluted water (Lu Yaoru, 1966). These hazards are economically important and cause difficult mining conditions, difficult construction and urban development. Anthropogenic activity, construction and development may enhance gypsum dissolution and karst formation aggravating the geohazards. Therefore, the study of gypsum karst is of practical significance.

The distribution and nature of the gypsum karst types in China is dependent on the distribution and genesis of the original gypsum deposits, their associated rocks and the local hydrological regime. Gypsum karst is particularly well-developed in the Ordovician gypsum of Shanxi and Hebei provinces where geological hazards associated with it have important consequences for coal mining. Gypsum karst is also developed in the Cambrian strata of Guizhou Province and the Triassic strata of Guizhou and Sichuan provinces. Enclosed drainage basins in the Qinghai-Xizang (Tibet) Plateau have extensive deposits of gypsum and other more soluble sulphates in which small-scale karst features have developed. Elsewhere in China, although gypsum is known to exist,

Fig. 1. Map showing the age and distribution of the main genetic types of gypsum in China. 1. Cambrian marine gypsum; 2. Ordovician marine gypsum; 3. Triassic marine gypsum; 4. Carboniferous marine gypsum; 5. Cretaceous lacustrine gypsum; 6. Tertiary lacustrine gypsum; 7. Late Tertiary-Quaternary lacustrine gypsum; 8. Thermal and metamorphic gypsum (typical localities); 9.Secondary deposits of gypsum produced by karstification (typical localities); 10. Coal mining areas affected by collapse columns caused by gypsum dissolution. Abbreviations for province names: An-Anhui, G-Gansu, Gg-Guangdong, Gi-Guangxi, Gu-Guizhou, H-Henan, Hb-Hebei, Hn-Hunan, Hu-Hubei, IM-Inner Mongolia, Ni-Ningxia, Qi-Qinghai, Sg-Shandong, Sh-Shanxi, Sx-Shaanxi, X-Xinjiang, Xi-Xizang (Tibet).

the gypsum karst features are not widely described and constitute an interesting area for future research. This paper seeks to document and review briefly the main developments of gypsum karst in China.

1. The genetic types and distribution of gypsum in China

Gypsum occurs in most of the provinces and autonomous regions of China. It is an important mineral resource that is widely mined and 90 percent of Chinese production comes from Shandong, Inner Mongolia, Qinghai, Hunan, Ningxia, Xizang, Anhui and Sichuan. The gypsum was formed in many different geological conditions which include: marine, lacustrine, thermal (volcanic and metasomatic), metamorphic, karst and other secondary processes (Lu Zhicheng, 1981; Tao Weiping, 1981). The simplified distribution, age and genesis of the main gypsum types in China are shown in Fig. 1 (Lu Yaoru, 1986, 1993; Chinese Institute of Geology and Mineral Resources, 1993).

Stratigraphical sequence of the karst aquifers of Shanxi Province (based on Zhang Shouquan, 1989, and Sha Qingan *et al.*, 1989)

Age	Formation	Lithology	Thickness (m)	Hydrological properties
Middle Ordovician	Fengfeng	Thick limestones and marls	20-70	aquifer
		Dolomite and marly limestone with gypsum and breccia	36-152	moderate aquifer
	Shang Majiagou	Limestone, marl and dolomite	150-200	main aquifer
		Dolomite, marl, brecciated limestone and gypsum	30-50	confinin g bed
	Xia Majiagou	Thick limestones and dolomites	90-130	aquifer
		Dolomitic mudstone and marl, sandy near base	30-50	confining bed
Lower Ordovician	Liangjiashan	Dolomite and marl	75-150	weak aquifer
	Yeli	Marly dolomite and limestone	30-60	confining bed

2. Gypsum karst in Shanxi Province and surrounding areas

In Shanxi Province gypsum is present mainly in the Ordovician Fengfeng Formation, but also to a lesser extent in the underlying Shang Majiagou Formation; below this lie the dolomites and marls of the Xia Majiagou, Liangjiashan and Yeli Formations (Table). The Fengfeng, Shang Majiagou and Xia Majiagou formations are the main aquifers in the region. The Fengfeng Formation contains up to about 60 percent of secondary gypsum, present as thick massive beds, nodular gypsum and gypsum interbedded with mudstone and dolomite (Sha Qingan et al., 1989). The Shang Majiagou Formation also contains some gypsum and is the major regional aquifer. In the Tiejingou deposit near Yangquan the Fengfeng Formation ranges in thickness from several tens to more than one hundred metres.

The current tectonic setting of the Fengfeng Formation has largely resulted from regional uplift and subsidence. Four belts can be recognised: an eastern plain at less than 50m above sea level, the Huabei Pinguan, extending into Hebei Province; the Taihang Shan mountains rising to 2000m; the main basin of the Shanxi Coalfield at 500-1200m above sea level; the Lüliang Shan mountains to the west of the coalfield rising to about 2800m above sea level. Within this part of China the rainfall is about 460mm per year with very high evaporation (Wei Keqin et al., 1989) so most of the active gypsum dissolution here comes from river seepage and groundwater flow (Zhang Shouquan, 1989; Pan Shulan, 1989). Some active gypsum dissolution is evidenced by the presence of sulphate in groundwater from springs, such as the Jinci Spring, situated along the faulted western margin of the Shanxi basin (Fig. 2). However, most of the gypsum karst is palaeokarst that has been uplifted or has subsided to its present hydrological position. The most impressive karst features are the collapse columns or breccia pipes that have developed in the Fengfeng Formation after the dissolution of massive gypsum and the collapse of the associated

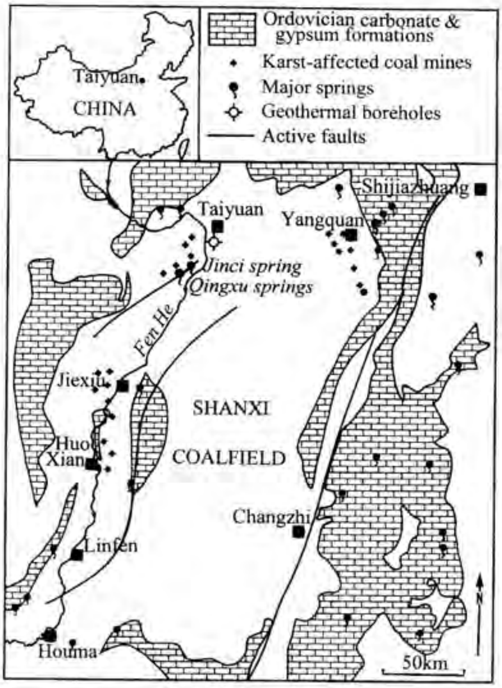

Fig. 2. The Shanxi coalfield and the locations of the main karst-affected coal mines and some important springs. The distribution of the Ordovician gypsiferous and carbonate sequences are shown surrounding the coalfield.

caves (Zhang Zhigan, 1982). The resultant collapse columns can be large, reaching many tens of metres in diameter and penetrating upwards through 50-500m of overlying strata (Fig.s 4 and 6) (Qian Xuepu, 1988). In addition to the massive collapse columns, the dissolution of gypsum and collapse of interbedded gypsum and carbonate strata has resulted in the formation of breccia layers that are commonly re-cemented with carbonate (Zhang Fenqi and Han Zingrui, 1983).

Boreholes in the Shanxi Coalfield basin show that anhydrite is generally present at depths of more than 800-1000m; it passes laterally up-dip into strata with gypsum. This in turn passes up-dip into gypsum karst breccias and collapse columns that, depending on the hydrological regime, are present from depths of about 300-600m to surface (Han Xingrui, 1991). The control of the gypsum karst by depth is responsible for the concentration of the coal mines with gypsum collapse columns around the margins of the coalfield in the Taiyuan, Huoxian and Yangquan mining areas (Fig. 2).

Several intervals of karstification have affected the gypsum of the Fengfeng Formation. In the Taihang Shan mountains, along the eastern side of the Shanxi Plateau, inclined collapse columns are present, but they have a perpendicular relationship with the associated strata. The inclination is assigned to the Yanshanian-Himalayan earth movements during the early Mesozoic, implying that much of the karstification predated that interval (Zhang Zhigan, 1980; Han Xingrui, 1991). These earth movements have been largely responsible for the uplift and subsidence of the gypsum karst so that collapse columns are now found at elevations of 700m above sea level in the Shanxi Plateau and depths of 700m below sea level in the Hebei Plane (Fig. 3). Subsequent karstification of the Shanxi Plateau and areas to the west was developed in the early Pleistocene when

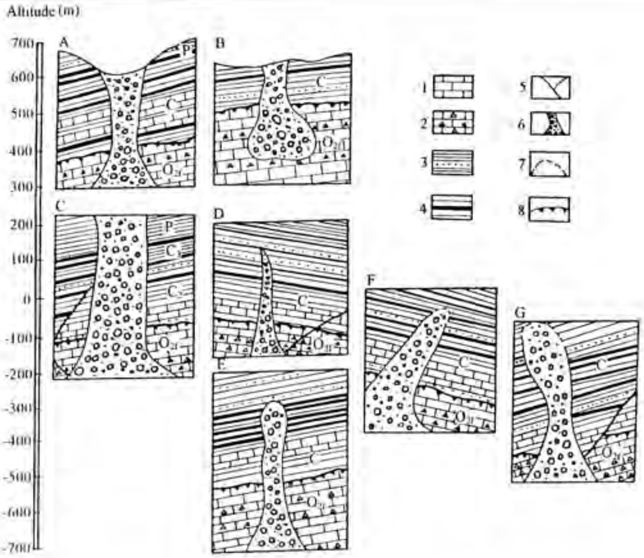

Fig. 3. Variations in the morphology and situation of collapse columns formed by the dissolution of Ordovician gypsum in the coalfields of northern China. The altitude variation of the different localities shows the effect of later tectonic activity. Collapse columns that reach the surface: A. Yangquan, Shanxi; B. Nianzhiguan, Shanxi; C. Jingjing No 5 Pit, Hebei. Collapse columns that only occur in the subsurface: D. Jingjing No 1 Pit, Hebei; E. Fengfeng No 9 Pit, Henan; G. Jingjing No 1 Pit, Hebei. Geological explanations: 1. carbonate rock; 2. breccia in carbonate rock; 3. shale and sandstone; 4. coal and clastic rock; 5. faults; 6. collapsed column; 7. conjectural boundary of collapsed column; 8. palaeokarst surface between the Ordovician Fengfeng Formation (O2f) and the Carboniferous (C2).

the water table was locally much higher. However, the area has now been uplifted further and the gypsum karst exists in the current vadose zone (Fig. 4). Within the Fengfeng Formation large palaeokarst caves, situated in the present vadose zone, have collapsed and are filled with breccia. Some of the collapse columns, such as those in the Nanyuan Mine of the Huo Xian area, are of Quaternary age (Qian Xuepu, 1988), and karst fissures are still undergoing dissolution and enlargement where there is active water flow.

3. Gypsum karst in Hebei Province

The gypsum karst of the Hebei Province forms an eastwards continuation of that seen in Shanxi Province. Collapse columns are present in the southern part of the Yan Shan mountains and in the coal mining area of the low-lying coastal plane where they cause mining difficulties (Fig. 3). At the Fangezhuang Coal Mine, 25 km ENE of Tangshan (150km ESE of Beijing) a breccia pipe filled with water-bearing collapse deposits was proved. It penetrated more than 300m upwards into the coal sequences from the underlying Ordovician carbonates and gypsum and had an open cavity at the top (Fig. 5). This palaeokarst structure allowed up to 12m^3/s of water to

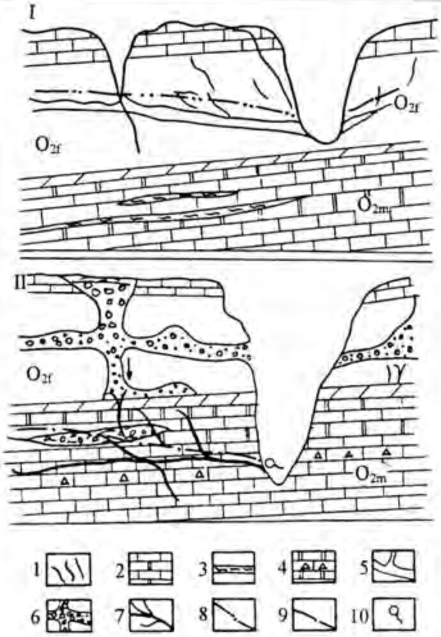

Fig. 4. The evolution of the gypsum karst in the Fengfeng Formation (Ordovician) gypsum of Shanxi Province. 1. The early karstification stage (early Pleistocene); II The recent karstification stage (post middle Pleistocene); 1. gypsum in the Ordovician Fengfeng Formation; 2. carbonate rocks; 3. gypsum interbedded with the carbonate rocks; 4. breccia in the carbonate rocks; 5. early karst cave passage in gypsum; 6. karst collapse column and breccia; later karstified cave-passage system in carbonate rocks; 8. early groundwater table in gypsum; 9. recent karst groundwater table in carbonate rocks; 10. karst spring; O2f Fengfeng Formation; O2m Majiagou Formation.

flood the mine. The total amount of karst water that entered the mine over three months was about 46 million cubic metres (Qian Xuepu, 1988) and surface collapses were associated with the dewatering. The Jingjing mine of west Hebei has also suffered serious water inrushes from encountering karst collapse columns.

4. Gypsum karst in Sichuan Province

Within the south-eastern part of Sichuan Province a thick collapse breccia after gypsum dissolution is present in the Jialingjiang "Series" of Triassic age. Breccia-filled collapse columns ranging from several to 60m in diameter have developed and migrated upwards into the overlying Jurassic coal measures. These collapse columns have penetrated several coal seams and cause difficult mining conditions in Hechuan County (Qian Xuepu, 1988).

5. Gypsum karst in other areas of northern China

In addition to the gypsum karst documented in Shanxi, Hebei and Sichuan Provinces, karst collapse columns are also developed in Shangdong, Inner Mongolia, Shaanxi, Henan and Jiangsu (Xiang Shijun, 1993; Liu Qiren et al., 1996). Like those in Shanxi Province, the collapse columns range from tens to several hundreds of metres across, and can be tens to hundreds of metres high. Stratigraphically they have been caused by the dissolution of Cambrian, Ordovician, and Triassic gypsum. The collapse columns penetrate the overlying strata of Cambrian, Ordovician, Carboniferous, Permian and Triassic age and locally cause hazardous mining conditions (Wang Rui, 1982; Li Jinkai and Zhou Wangang, 1988).

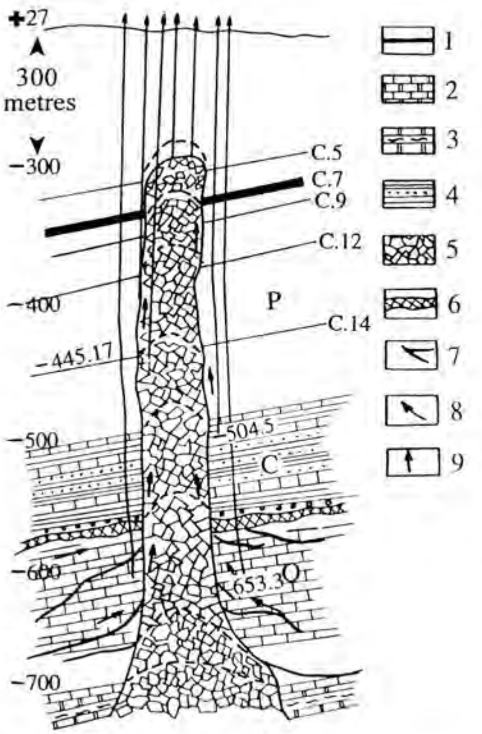

Fig. 5 Cross-section through a large collapse column filled with breccia at the Fangezhuan Mine near Tangshan.
1- Permian Shanxi Formation;
2- carbonate rocks;
3- carbonate rocks with gypsum;
4- sandstone and shale;
5-collapse column showing various stages of its upward progression;
6-palaeokarst horizon between the Ordovician and Carboniferous sequences;
8- direction of water flow;
9- boreholes.
Compiled from borehole data of the Bureau of Kailuan Mine (Xiang Shijun et al., 1993; Liu Qiren et al., 1996).

6. Gypsum karst in Guizhou Province

In South China sub-tropical climatic conditions have existed for a long time. Within the Suiyang area, situated to the north of Guizhou Province, there is a mixed limestone and gypsum karst developed in the Middle Cambrian Shilengshui Formation of the Luoshanguan Group. In the Shilengshui Formation, thick and medium beds of gypsum total more that 10m in thickness. Both the gypsum and the carbonates have been karstified for a prolonged period, and gypsum within an area of 5 km by 3 km has largely dissolved. Some of the gypsum has subsequently been redeposited as secondary gypsum in the vadose zone of the Shigao Dong Cave developed in the carbonates of the Luoshanguan Group. Shigao means gypsum in Chinese, and the secondary gypsum deposits here have been exploited by the local people for more than one hundred years.

Guizhou Province has well-developed Fenglin (cone) karst in the Triassic limestone sequences, but gypsum is also present. Near to Puding (about 90km SW of Guiyang and 20km west-north-west of Anshun) there is a mixed gypsum and limestone karst developed in the Middle Triassic Guanling and Yingling Formations. The Yingling Formation is the lowest, and contains up to 10m of gypsum and breccia beds in units up to 1.5m thick. The overlying Guanling Formation includes some gypsum, but also breccia after gypsum dissolution. The Huoshipo Dam here has suffered serious leakage through the gypsum karst beneath it (Hu Wuzhou, 1988; Lu Yaoru and

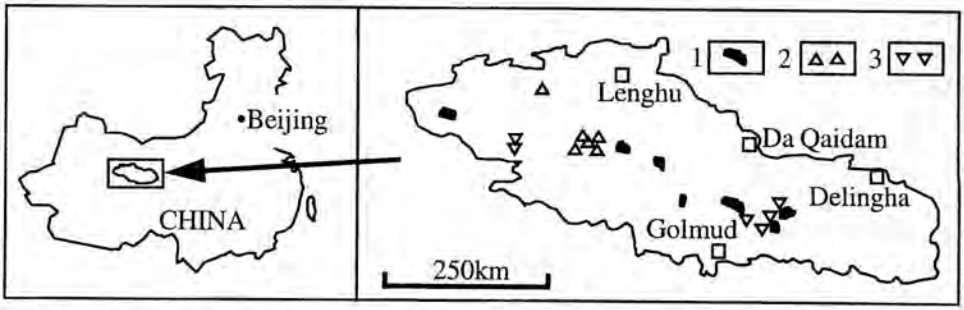

Fig. 6. Gypsum deposited in the Chaidamu Basin of Qinghai: 1 - recent salt water lake; 2 -Early Pleistocene gypsum deposits; 3- Late Pleistocene gypsum deposits.

Cooper, in press). The Yangmazhai Reservoir near Langdai and the Mahuangtian Reservoir near Guanling also have similar leakage problems (Hu Wuzhou, 1988).

7. The gypsum-salt lake karst of the Qinghai-Xizang Plateau

In the Qinghai-Xizang (Tibet) Plateau and in Northwest China there are a number of enclosed saline basins with salt lakes containing sulphate-rich water. Analyses of the lake waters (Lu Yaoru 1986, 1996; Zhang Xiyu, 1988) shows that they have concentrations of sulphate between 2,332-90,610 ppm in the Xizang Plateau lakes and 20-37,440 ppm in the Chaidamu Basin of Qinghai. Within these lake basins deposits of gypsum are associated with complex soluble sulphate salts of Na, Mg, K, and Ca including thenardite, mirabilite, epsomite, syngenite and hydroglauberite. During the wet season small-scale karst phenomena form rapidly in the gypsum and other salts which as they are dissolved; these salts get redeposited later during the dry evaporitic season. In addition to the annual climatic variation, uplift of the Qinghai-Xizang Plateau since the Quaternary has affected the climate and reduced the precipitation. This has caused the initially large salt lakes, such as the Chaidamu Basin, to dry out considerably so that only small salt lakes now exist (Fig. 6). Within this basin extensive layered gypsum deposits of Pleistocene age are present and these have developed gypsum karst features which include corroded flutes, fissures with a few small caves and passages which readily collapse.

8. Thermal and biogenetic-chemical gypsum karst

Thermal (volcanic and metasomatic) and biogenetic-chemical gypsum are minor components of the Chinese gypsum karst. Gypsum of thermal origin occurs as replacement deposits, an example being the Daye gypsum deposit in Hubei Province. Gypsum of volcanic origin occurs in the Ma'an Shan gypsum deposit in Anhui Province. In areas of hydrothermal activity, hot deeply circulating groundwater can corrode the gypsum deposits and develop thermal karst features. There are many sulphate-rich geothermal springs, such as the Chongqing spring, (50km west of Chengdu, Sichuan Province) emanating from the Triassic carbonate and gypsum rocks. In the south of Sichuan Province there are Tertiary deposits of native sulphur associated with carbonates and gypsum. These deposits were formed by biogenic processes acting on gypsum and have karst holes, small caves and passages associated with them.

Acknowledgements

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Place names

The translation of Chinese place names to Pinyin (western script) can be variable. The main spellings used in this paper have been taken from the Chinese Atlas: Zhonghua Renmin Gongheguo Fen Sheng Dituji (Hanyu Pinyinban) Ditu Chubanshe, Zhongguo Beijing, 1977. Where the places mentioned are not in the atlas they have been located relative to a larger named place.

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