Chapter II.1

Gypsum karst of the World: a brief overview

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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 Zuhashchenko, (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 lc 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 intercalatior dolomite, clay and marl, influence the shape of passage cross-sections.

Locally, the upper gypsum member is removed by erosion, and the plateau surface compı 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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