Chapter I.6

HYDROGEOLOGY OF GYPSUM FORMATIONS
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Introduction

The hydrogeology of any karst aquifer is largely a function of the general hydro-stratigraphi-cal/recharge-discharge configuration (boundary conditions) and of the structure of secondary kar-stic porosity. Both of these should be considered as being variable in time, in a response to chan-ging geomorphic conditions and the "internal" development of a karst system. Hence, the evolu-tionary 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 achie-ved 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 appli-cable only to areas of barren exposed karst type.

General details of the evolution of gypsum karst and descriptions of its main types are outli-ned 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 confi-ned 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 den-dritic 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 1.5). 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 1.9 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
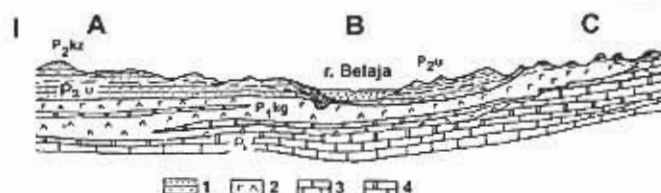
Western flank of the Bashkirsky dome and the Birsky depression (After Hydrogeology of the USSR..., 1972). 1 = clay, sandstone and marl, 2 = gypsum and anhydrite, 3 = limestone, 4 = dolomite.
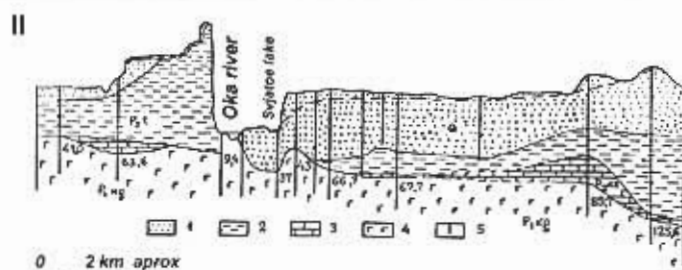
Dzerzhinsky city area in the Volga-Kamsky region (After Karst phenomena..., 1960). 1 = sand, 2 = clay, marl and shale. 3 = limestone, 4 = gypsum and anhydrite, 5 = boreholes. Numbers indicate the depth to the top of gypsum.
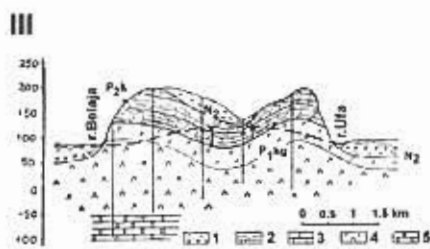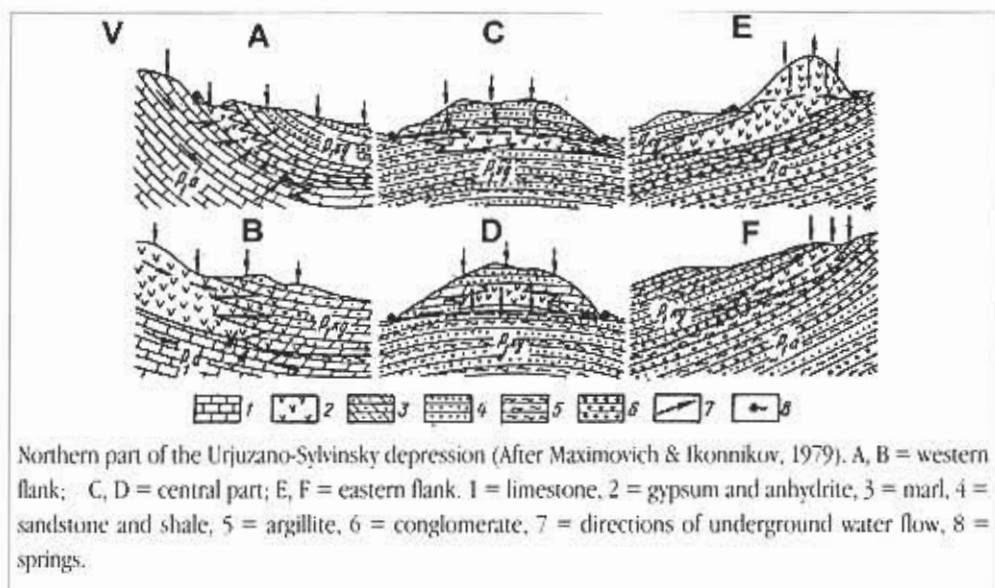

Ufimsky plateau (After Kudrjashov & Martin, 1970). 1 = alluvial deposits, 2 = clay, argillite, sandstone, 3 = limestone, 4 = gypsum and anhydrite, 5 = dolomite. Dashed line indicates potentiometric level of groundwaters.

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 pre-existing 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 nor-

mally 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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