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.

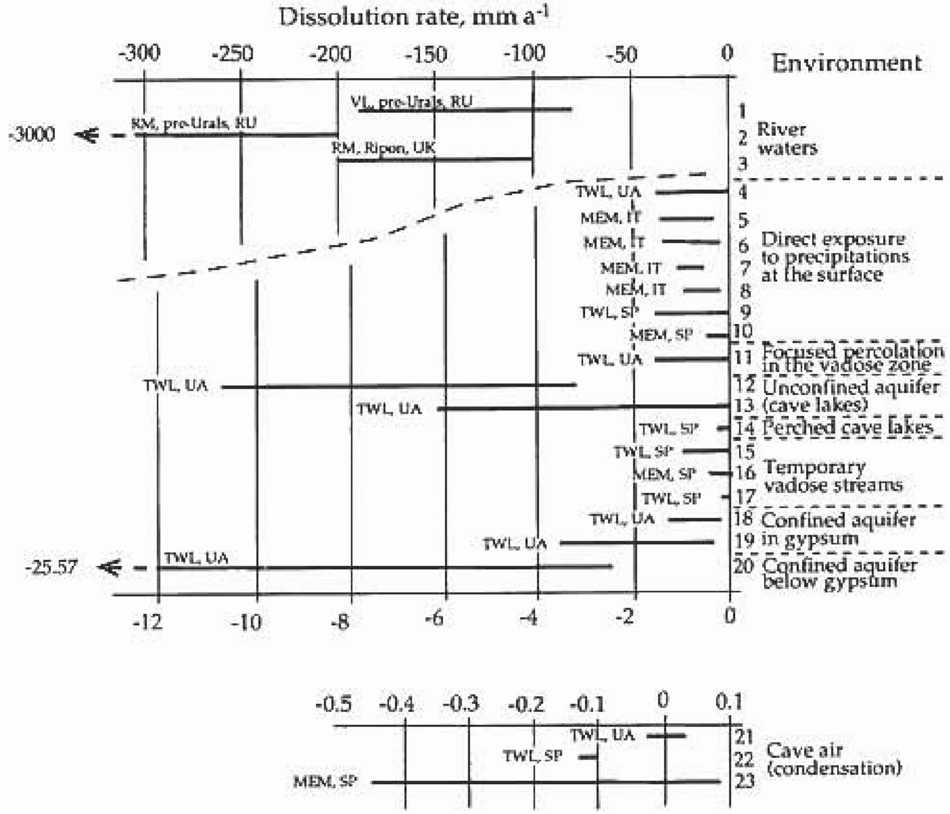

Fig. 1. Gypsum dissolution rates in different regions and environments. Numbers on the bars correspond to the dataset numbers in the Table. Methods: RM = retreat measurements, VL = volume loss, TWL = tablet weight loss, MEM = micro-erosion meter.

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 1.4). 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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