Chapter I.9

WEATHERING CRUST AND KARREN ON EXPOSED GYPSUM SURFACES

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Abstract

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

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

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

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

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

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

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

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

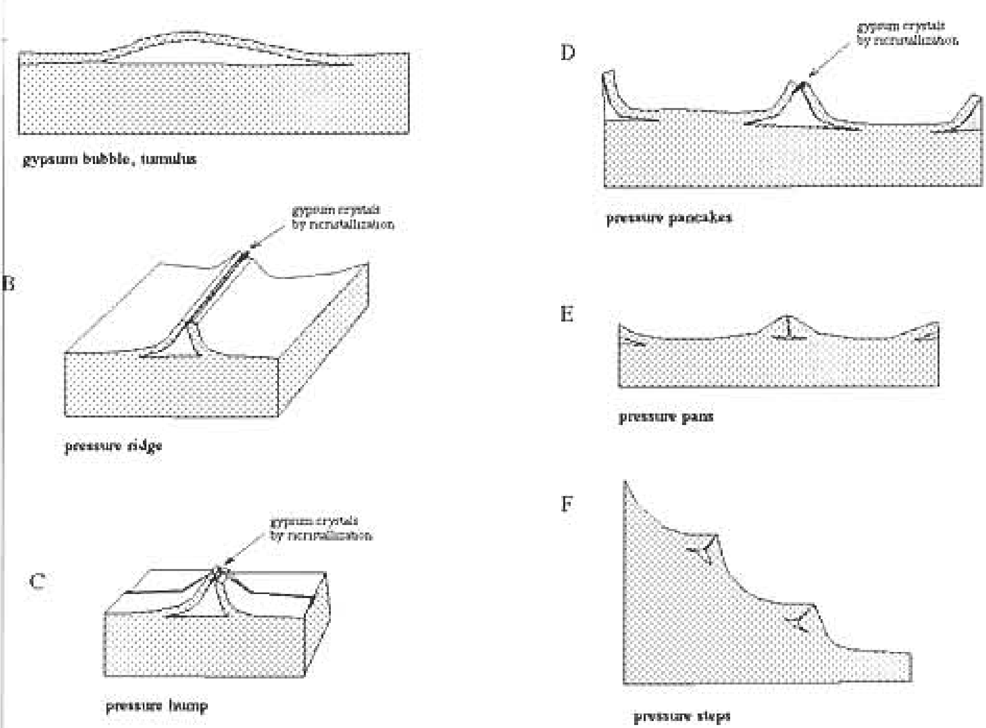

Fig. 1 - Morphological types recognised on the on the "weathering crust" of the exposed rocky surfaces of Sicily: a) the rocky polygons, often with bended fringes, b) the gypsum bubbles, c) the pressure ridges, d) the pressure humps, e) the pancakes, f) the pressure pans and the pressure half pans, g)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

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

2. Forms produced by dissolution

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

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

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

2.1. Nano-forms

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

2.2. Micro-forms

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

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

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

2.3. Small dissolutional forms

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

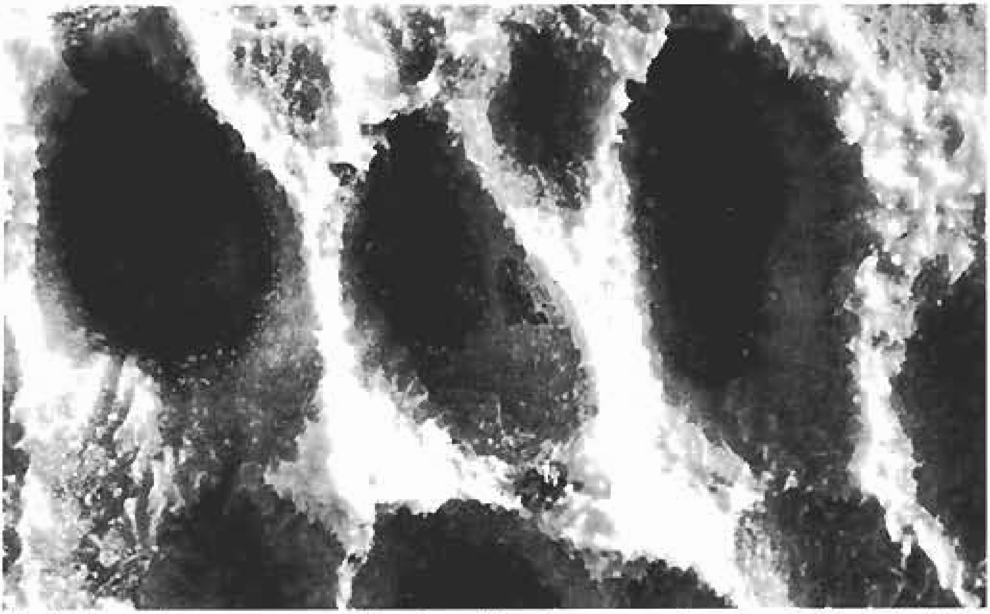

Fig. 2 - Minute rain craters on gypsum. The slopes of the minute craters show microrills (Verzino, Calabria, Italy).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.4. Meso-forms

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

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

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

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

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

3. Genetic aspects

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

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

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

KARREN IN EVAPORITIC ROCKS: SKETCH OF CLASSIFICATION

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

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

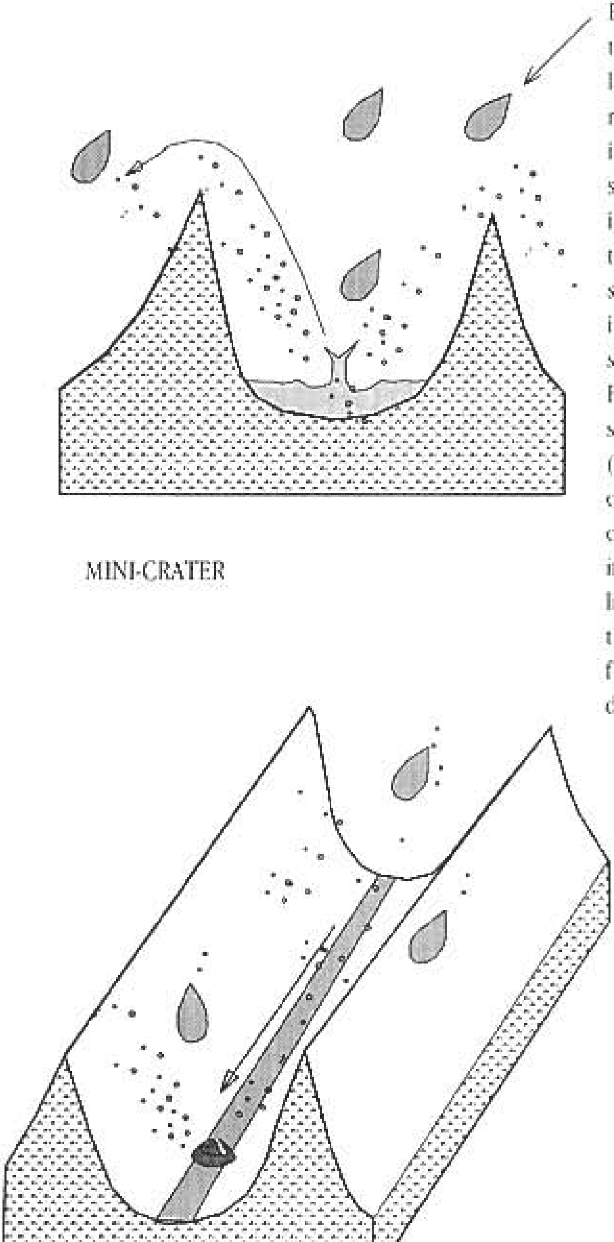

Fig. 5. The genesis of mini- rain craters is probably due to "splash dissolution" (figure above). The impact of raindrops focuses dissolution in the inner part of the depressions. Very small drops resulting from the impacts and the water collected on the crater floor are ejected by successive impacts.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

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

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

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

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

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

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

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

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

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

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

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

4. Problems of classification and final remarks

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

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

- in gypsum, karren evolution is governed by specific weathering phenomena as well as by the dissolutional process;

- fractures in gypsum only rarely evolve as fissures and grikes that open to the surface; pits and shafts are rare, so epikarst is limited;

- runnels are not very common on gypsum, especially on macro-crystalline gypsum, where development is locally guided by the orientations of the long axes of crystals;

- biological processes related to pioneer vegetation and soils do not facilitate gypsum dissolution and may instead perform a protective function on the rocky surface, as do some lichen colonies;

- stone heaps and chaotic blockfields (griza), typical on some carbonate karst areas, are missing in evaporite landscapes, though some types of pavements and pinnacle karst are present.

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

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