Suppl. Geogr. Fis. Dinam. Quat.
III, T. 4 (1998), 91-99, 13 figg., 1 tab.

FOURTH INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY - Italy 1997

Karst Geomorphology

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ASPECTS OF WEATHERING AND LANDFORMS EVOLUTION ON GYPSUM SLOPES AND RIDGES OF SICILY

ABSTRACT: MACALUSO T. & SAURO U., *Aspects of weathering and landforms evolution on gypsum slopes and ridges of Sicily*. (IT ISSN 0391-9838, 1998).

In Sicily, on the rocky outcrops of the gypsum, it is possible to recognise a weathering crust, which is often evidenced by a polygonal pattern and by some gypsum bubbles. The crust is the consequence of the phenomenon of expansion of the outer layer of the gypsum.

The main forms of the crust are described as gypsum bubbles, pressure ridges, pressure humps, pans, pancakes, and steps.

The evolution of the crust seems to be linked to a mass transfer by solution inside the outer gypsum layer and to the growth of crystals; these are controlled both by the seasonal cycle of the pore water and by single event cycles determined by rainfall episodes during the summer season.

The dynamics of the crust also influences the evolution of larger forms as the «mega bubbles», and the domelike hills, minimising the influence of the pre-existing structural elements.

KEY WORDS: Gypsum Karst, Weathering Crust, Gypsum Positive Landforms, Sicily.

INTRODUCTION

Most of the papers dealing with the geomorphological evolution of surfaces in gypsum rocks analyse the erosional forms originated by mass wasting, and fluvial and karstic processes. In particular one can find information about landslides, fluvial valleys, blind valleys, dolines and karren.

The aim of this paper is to discuss relatively neglected aspects related to the weathering *latu sensu* of the outer layer of the gypsum rock, especially in correspondence of the denuded slopes and ridges.

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On gypsum rock slopes it is possible to recognise two very different weathering environments:
1. the soil-gypsum interface, where the rock surface is «protected» by a soil pellicle;
2. the bare gypsum surface directly exposed to the atmosphere.

In the type 1, if the soil is permeable and water circulates inside it, covered type karren, very similar to those in limestone (Rundkarren type), develop. It is possible to observe fine examples of Rundkarren on recently denuded rocky surfaces in the Santa Ninfa area.

In the type 2 there is a large variety of free karren, which have been described in previous papers (Macaluso & Sauro, 1996, 1997) and are not discussed in this article.

In fact, the connection between the presence of a «weathering crust», evidenced by peculiar forms, and some larger domelike forms, on which this crust is developed, is surprising.

THE FORMS OF THE «WEATHERING CRUST»

In western Sicily the gypsum of the evaporitic sequence of the Messinian age (Upper Miocene) outcrops on a large area and presents different lithofacies as the selenitic, alabastrine, laminated balatino and detritic. Large rocky surfaces are without soil cover, as a consequence of the soil erosion induced by forest clearing, fires, sheep and goat grazing. Because of the high solubility of these rocks a large variety of surface and underground forms have evolved.

The climate regime is of Mediterranean type with a remarkable seasonality of precipitation. In the studied area the average annual precipitation is around 650 mm, with about 80% of rainfall in the autumn-winter semester, and

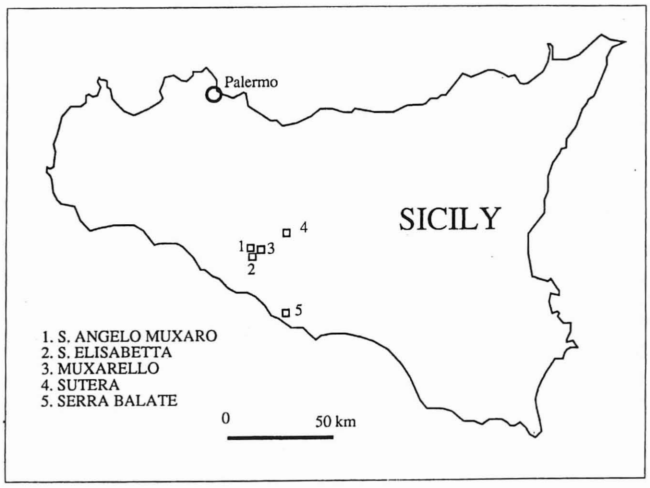

FIG. 1 - Location of the studied areas.

only 5% during the trimester June, July, August. The average annual temperature is 15°C. During the summer period the temperature may exceed 40°C.

The «weathering crust» is better developed on bare rocky surfaces in selenitic gypsum (macro crystalline gypsum, with crystals ranging from one millimetre to more than 10 cm) and it is marked by distinctive forms.

Among the most interesting areas where this crust is recognisable is the large slope of Serra Balate, south west of Palma di Montechiaro and some exposures nearby Sant'Angelo Muxaro (Cozzo Impiso) and Sutera (fig. 1).

The two main «morphostructures» characterising the «weathering crust» are:

1. «polygons»;
2. «bubbles».

These morphostructures are the expression of an increase in volume of the outer rocky mass with a thickness ranging from some decimetres to some metres.

The development of this crust is not controlled by the bedding or by other structural features, even if sometimes polygons and bubbles may coincide with the bedding and one or more sides of certain polygons correspond to previous fracture lines.

Inside the crust there is a clear evidence of the tendency to the sealing of both the bedding planes and the fissures.

The more frequent morphological types, recognised on the rocky surfaces and generally linked to the evolution of the above mentioned morphostructures, are the following (fig. 2):

a) gypsum bubbles;
b) pressure ridges;
c) pressure humps;
d) pressure pans and pressure half pans;
e) pancakes;
f) steps.

Gypsum bubbles are domelike reliefs ranging from some decimetres to about 15 meters in diameter and a few centimetres to several decimetres in height. These structures consist of a circular «shell» of gypsum uparched above a cavity (fig. 3).

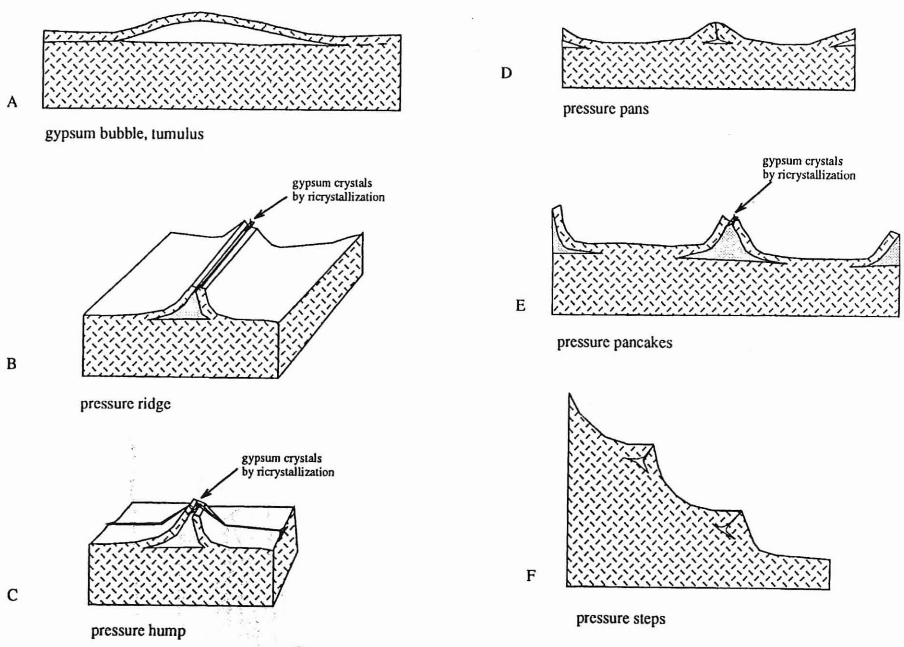

FIG. 2 - Main morphological types recognised on the «weathering crust» of the exposed rock surface.

FIG. 3 - A large bubble and the opening of the small cave grown inside it. Even if the bubble is very large (about 11 m in diameter), the thickness of its shell is modest (about 20 cm) (photo by U. Sauro).

Observations on a limited number of bubbles of Serra Balate show that there is a good correlation between diameter and height (fig. 4) but not between diameter and thickness of the outer «shell» (see table 1).

TABLE 1 - Size of some gypsum bubbles of Serra Balate

diameter	minimum diameter	hight	maximum height	thickness	D/h ratio	D/th ratio
70	•	20	•	•	3,500	
120	•	30	•	•	4,000	
130	•	15	•	•	8,667	
170	•	35	•	20	4,857	8,500
230	•	36	•	20	6,389	11,500
250	•	75	•	•	3,333	
300	•	55	90	40	5,455	7,500
320	•	50	•	•	6,400	
450	•	70	•	25	6,429	18,000
500	•	75	•	25	6,667	20,000
520	440	72	•	32	7,222	16,250
1100	•	88	•	20	12,500	55,000

The bubble's shell may correspond to a bed (as in Serra Balate), or be discordant from the bedding. Where the slope corresponds to the bedding it is easier to find large forms. With time the «roof» collapses and the cavity becomes open on the surface. Small bubbles may also develop in the central part of some polygons.

Pressure ridges arise between two polygons and they are formed by their two margins being bent upwards. Their heights range from a few millimetres to some decimetres according to the lithological control, the morphology of the surface, and the evolutionary stage of the form.

Pressure humps are nearly pyramidal or conical exposures from a few decimetres to more than one meter high. They develop in correspondence with a junction point of the borders of three or four polygons (fig. 5).

Pressure pans and pancakes are closed or nearly closed basins, each developed inside a polygon with the margins bent upwards. While in the pressure pans the borders are single ridges, in the pancakes the borders of the two contiguous polygons are separated and they give birth to two small sub parallel banks. Their heights range from a few millimetres to some decimetres.

The steps are similar to the pans and/or the pancakes but develop on steep slopes which originate stairlike features.

Some polygons are uparched in their central part forming a bubble.

In the Serra Balate area different types of karren as Rillenkarren, Rinnenkarren and Mäanderkarren are overlapped on the polygons and the bubbles. Such solution forms are generally infrequent in selenitic gypsum.

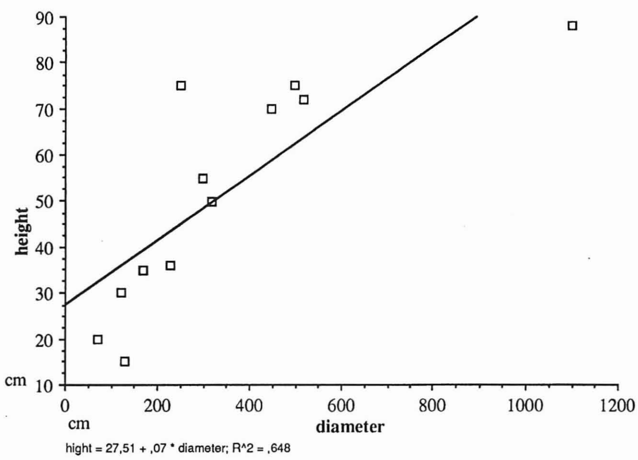

FIG. 4 - Scattergrams of a limited number of bubbles of Serra Balate. A good correlation between diameter and height is evident.

FIG. 5 - A large pressure hump with a nearly conical form. The form has been able to entrap clastic sediments, which now prevent the collapse of the structure (photo by U. Sauro).

THE «WEATHERING CRUST»

The forms described above are expression of dynamic fields of pressure acting inside the outer rocky layer.

In the past many authors have tried to explain the origin of the bubbles proposing different models. Calaforra (1996) lists three main hypotheses:

1. the hypothesis of a «tectonic» origin, which explains the development of the bubbles with recent tectonic stresses;
2. the hypothesis of volume increase, based on the mineralogical anhydrite - gypsum transformation;
3. the hypothesis of the role of solution and precipitation processes, which allows for re-crystallisation phenomena.

In discussing the three models, he states that it is easy to demonstrate that hypotheses 1 and 2 are incorrect. In contrast, hypothesis 3 could be a good explanation of the origin of the bubbles.

In fact, hypothesis 3 explains not only the origin of the bubbles and of the polygons but also the origin of larger forms like mega-bubbles and domelike summits.

Fig. 6 is a model of the processes of solution and precipitation in the weathering crust, which could bring about an increase of volume. It is not difficult to explain migration and precipitation of gypsum if one consider a climatic regime like the Mediterranean one with seasonal alternation of water surplus (wet winter season) and water deficit conditions (dry summer season).

The rainfall starts an overland flow, the water dissolves the gypsum on the surface (A) while part of the water solution manages to penetrate inside the pores of the rock. The solution reaches saturation (with $CaSO^4$) on the surface or a few millimetres inside the rock (the B line can be considered a saturation front). The solution continues to penetrate both inside the pores and in the fissures (2) reaching a front of porosity water (C). The water may also flow laterally (3). During the dry season the solution looses water by evaporation (4). The inner solution becomes oversaturated and moves by capillarity towards the surface (5). In the D zone there is precipitation of gypsum by an increase in crystal's size and/or by development of new crystals. In the fissures filled with fine grained materials new gypsum crystals may develop. The mass transfer from the inner towards the outmost zone results in pressure relaxation (6) in the C zone and in pressure increase (7) in the D zone.

This mechanism represents a way of mass transfer from the outmost gypsum layer (very thin due to the high solubility of the gypsum) towards a more inner gypsum layer. The thickness of this layer is probably related to the grain size of the gypsum and ranges between a few decimetres (alabastrine gypsum and gypsarenites) to a few metres (macrocrystalline gypsum consisting of very large crystals).

A mechanism of this type could also be hypothesized for a thinner layer in connection with single rainfall events, especially during the summer period.

When a fissure unfolds along a ridge, the overland flow transports soil particles and grains of other insoluble rocks inside the split. The fissure becomes a trap for sediments, but the evolution of the ridge may squeeze out the fillings. New crystals growing at the interface between the filling and the rock may be observed.

It is possible to verify this type of evolution in the area of Serra Balate where there is an artefact made with gypsum stones covering a concrete vault above a pit for water. In a period of a few decades the stones have «enlarged» laterally and are now fused together as a consequence of crystals growth, fed by the mass transfer from the surface towards the inner part.

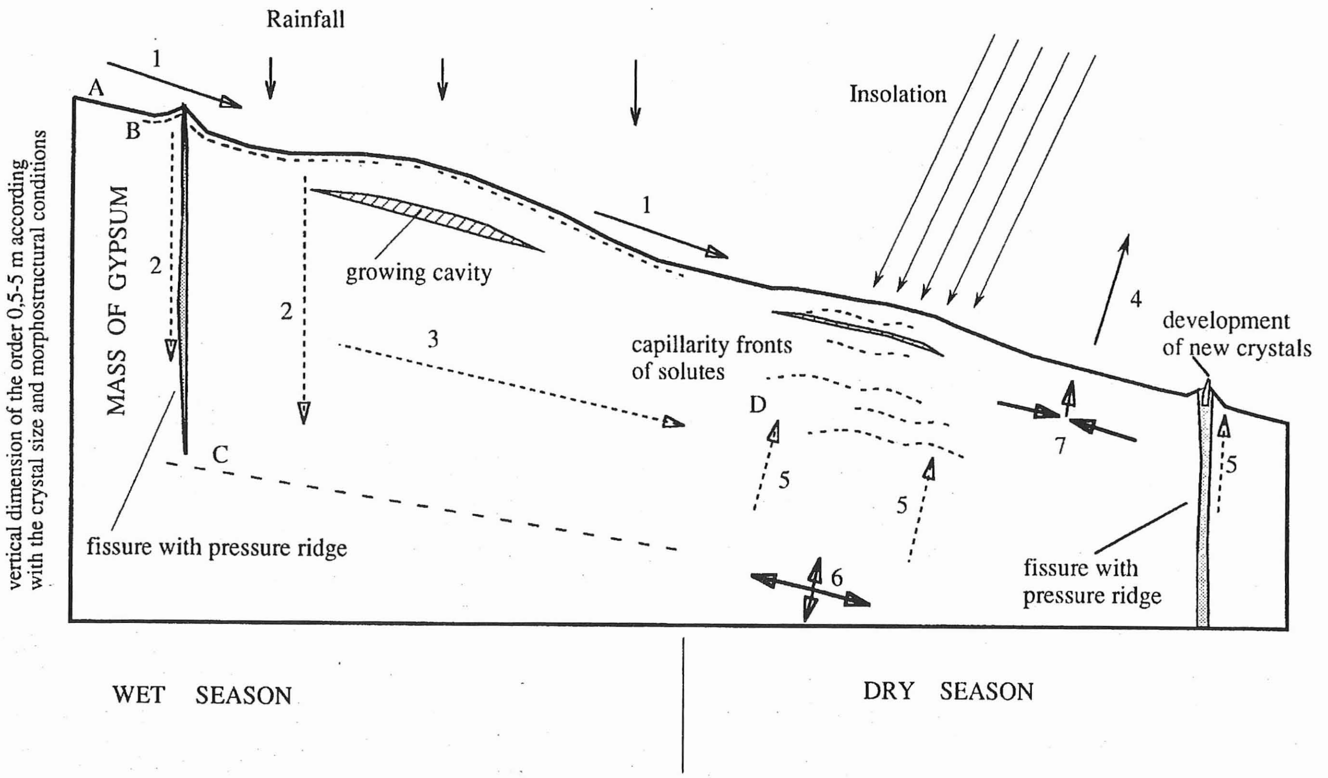

FIG. 6 - Sketch of the main processes occurring inside the outer gypsum layer during the wet (winter) and the dry (summer) season. The rainfall starts an overland flow and the water dissolves the gypsum on the surface (A) while part of the water solution manages to penetrate inside the pores of the rock. The solution reaches saturation (with $CaSO^4$) on the surface or a few millimetres inside the rock (the B line can be considered a saturation front). The solution continues to penetrate both inside the pores and in the fissures (2) reaching a front of porosity water (C). The water may also flow laterally (3). During the dry season the solution looses water by evaporation (4). The inner solution becomes oversaturated and moves by capillarity towards the surface (5). In the D zone there is precipitation of gypsum by an increase of the crystals size and/or by development of new crystals. In the fissures filled with fine grained materials new gypsum crystals may develop. The mass transfer from the inner towards the outmost zone results in pressure relaxation (6) in the C zone and in pressure increase (7) in the D zone. This mechanism represents a way of mass transfer from the outmost gypsum layer (very thin due to the high solubility of the gypsum) towards a more inner gypsum layer. The thickness of this layer is probably related with the grain size of the gypsum and ranges between a few decimetres (alabastrine gypsum and gypsarenites) and a few metres (macrocrystalline gypsum consisting in very large crystals).

THE PROBLEM OF MEGA-BUBBLES AND OF DOMELIKE FORMS

In some areas the exposures of a weathering crust coincide with larger forms resembling the bubbles. In fact «mega-bubbles» and domelike hills exist. The «mega-bubbles» are some tens of metres in diameter and some metres heigh. The domelike hills show different sizes ranging from some tens to some hundreds of meters in diameters. On all these forms a well developed polygonal crust is recognisable.

A spectacular group of «mega-bubbles» or small domes are part of a complex ridge near to the «Salamone» houses not far from Muxarello on the road to Sant'Angelo Muxaro (fig. 7). It is not possible to observe the inner structure of these forms except for a road cutting the margins of some bubbles. Nevertheless, on the mega-bubbles surface, in correspondence with the connection of the borders of some polygons it is possible to find open cavities allowing water to flow towards the interior of the structures.

The summits of many large hills in gypsum present a domelike geometrical form, similar to that of the mega-bubbles (figg. 8, 9, 10). These forms are not controlled by the strike, the dip or the fissuring of the gypsum beds. On most of the dome summits a polygonal fissuring with pressure structures underlines that the outer layer is evolving as a «weathering crust» characterised by processes of volume increase.

The genesis of this type of form is surely the expression of a homogeneous behaviour of the rock in comparison with the erosional processes. This form may remind some domelike summits in granite rocks. Probably, it is just the formation of the «weathering gypsum crust» which favours the development of the domelike form through the creation of isotropic field of radial stresses with reference to the central part of the relief. The weathering crust minimi-

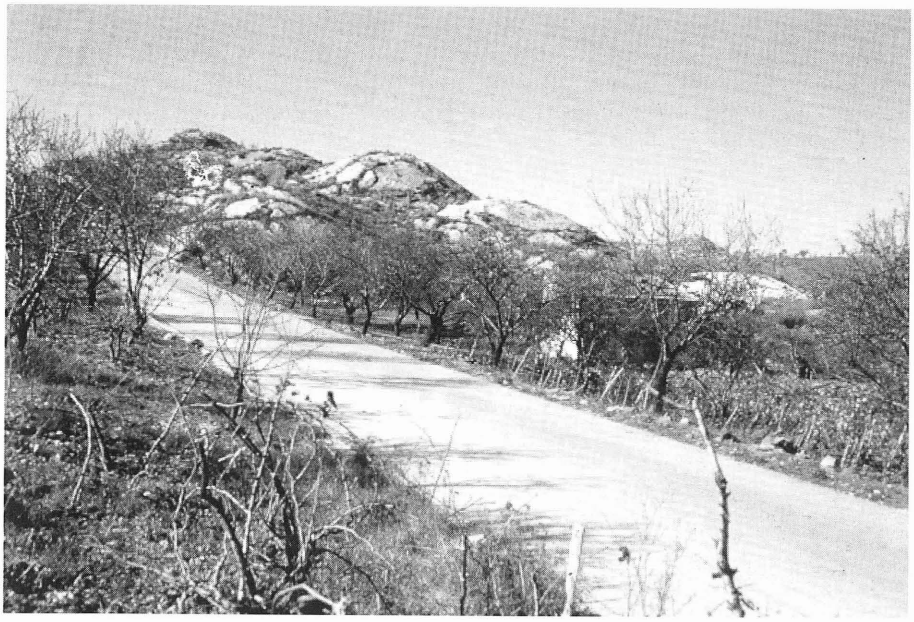

FIG. 7 - Intermediate forms between mega bubbles and small domelike structures near case Salamone. The polygonal structure of the «crust» is evident (photo by U. Sauro).

ses, in this way, the influence of pre-existing structural elements, such as bedding planes and fractures (fig. 11).

It is possible to observe two different type of crust dynamics. In the large homoclinal slope, as that of Serra Balate, the crust coincides with one or more beds, with expansion leading to the development of forms like bubbles, polygons and related forms; here no domelike summits develop. Where the gypsum beds or fractures do not coincide with the crust, this, as a new structural element, tends to favour the development of domelike summits and to neutralise the influence of the pre-existing structural elements. In the first case there is congruence between the structural influence and the crust evolution, while in the second situation there is incongruence (figg. 12, 13).

In relation with the existence of this weathering crust, the epikarst in gypsum is not well developed. However, locally absorbing cavities exist inside both bubbles and pressure ridges. An interesting aspect of this epikarst is that

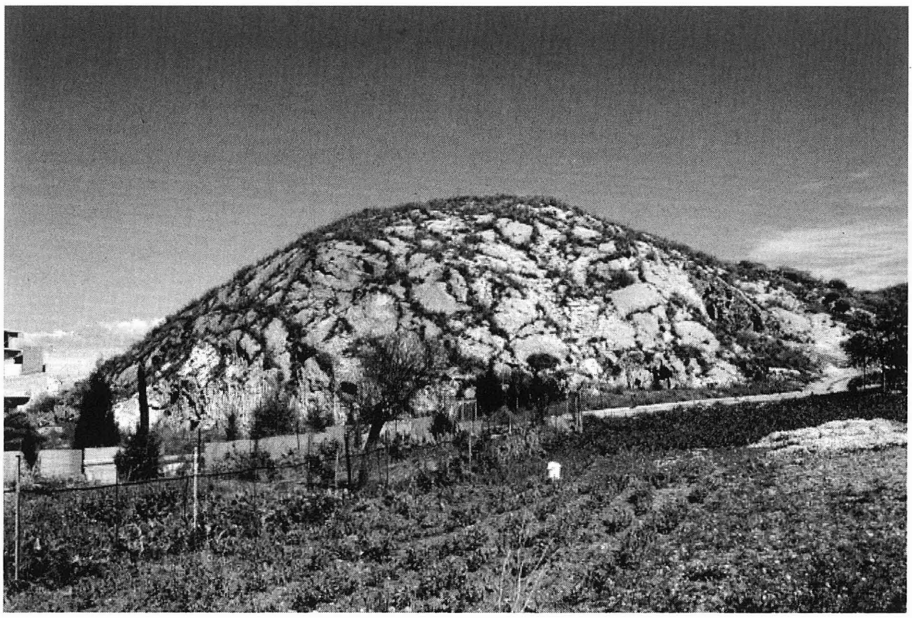

FIG. 8 - The domelike structure of Monte Impiso near Sant'Angelo Muxaro. The outer surface is characterized by a «crust» evidenced by a polygonal pattern of small ridges and fissures (photo of M. Macaluso).

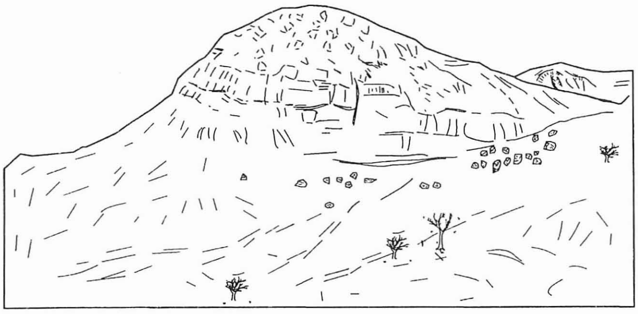

FIG. 9 - A domelike hill visible from the road Sant'Angelo Muxaro - S. Elisabetta. The bedding is subhorizontal while the fissuring is vertical. These structural elements have not influenced the evolution of the crust on the summit (sketch drawn from a photo by M. Macaluso).

most of the pre-existing discontinuities are sealed near the surface but they tend to be open at the depth of a few meters. This aspect is in accordance with the model of volume increasing of the crust.

SOME CONCLUDING REMARKS

The causes of character changes of the outer rock layers are not yet well explained. The explanation provided by most Authors, seeing them as the result of transformation of anhydrite in gypsum is incorrect. In fact, the mineralogical analyses carried out in some of the studied areas reveal that anhydrite is present in a very small amount not only near the surface but also in the caves.

There are other physico-chemical processes that could explain the change in volume and the development of the weathering crust near the surface:

- the recrystallization of gypsum in connection with the cycles of the porosity water;
- an increase of porosity as consequence of tensional relaxation;
- plastic deformation linked to a rearrangement of crystalline structure;
- the phenomena of thermal dilatation and contraction;
- gypsum-bassanite transformation;
- some combination of more of the above mentioned processes.

During the development of all the forms typical of the weathering crust, other processes should also be considered, such as:

- the solution of the gypsum;
- fragmentation such as the detachment of gypsum crystals (granular disintegration) or of larger rock pieces;
- overland flow and the creep.

Even if all these processes coexist, the main role seems to be played by the recrystallization of gypsum in connection with cycles of the porosity water. These cycles may be not only seasonal (seasonal cycle) but also linked to single rainfall events (single event cycle), especially during the summer periods.

While the seasonal cycle may affect a considerable thickness of the rock, the single event cycles affect only a thin layer. In this sense the seasonal cycles play an important role in the evolution of the weathering crust as a whole and of the domelike summits, while the single event cycles concern mainly the evolution of the small and shallow forms as the bubbles and the polygons.

The lifetime of a small form like a bubble is probably of the same order of that of the life of a man, between a few years and several decades. The time of formation of a domelike summit is of the order of thousands of years.

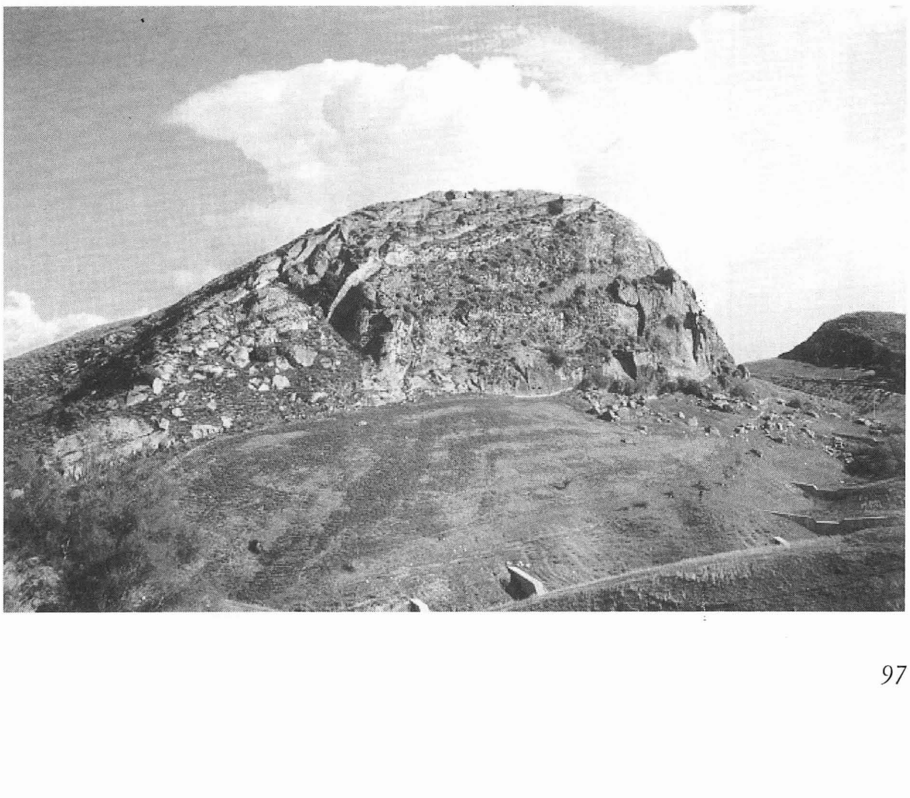

FIG. 10 - A half-dome visible from the road Sant'Angelo Muxaro - S. Elisabetta. The bedding is vertical and it has not influenced the evolution of the crust. The bedding scarp is evolving by toppling phenomena (photo by M. Macaluso).

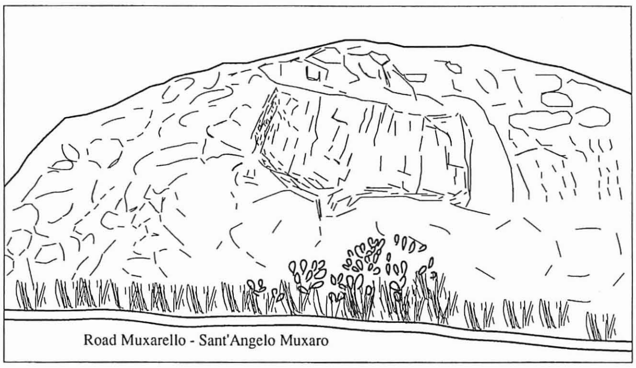

FIG. 11 - Detail of the slope of Monte Impiso. In the small quarry in the foreground the nearly vertical bedding is recognisable. It does not influence the evolution of the outer surface. Near the surface the bedding planes are closed but they may be open some meters down (sketch drawn from a photo by M. Macaluso).

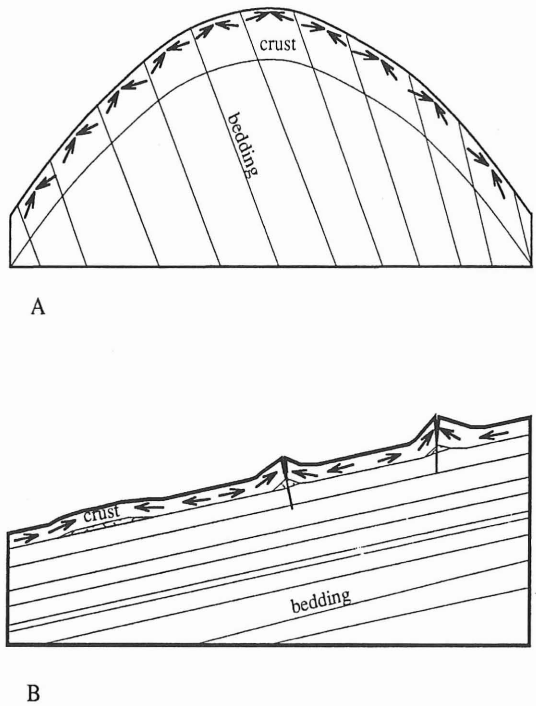

FIG. 12 - Sketch of two different types of dynamic of the crust. In a domelike summit the crust, as a new structural element, tends to neutralise the influence the pre-existing structures. In a large homoclinal slope the crust coincides with one or more beds and the expansion causes the development of forms like bubbles, polygons and related forms.

When a combination of the above mentioned processes occurs, it is possible that it assists in accelerated weathering of the surfaces.

Given the fact that the basic conditions for the development of the weathering crust are: lack of a soil cover, which is very often a consequence of human impact since protohystoric times (a), and the alternation of water saturation and dryness conditions in the superficial porosity zone of the rock (b), the weathering crust may be considered both a morphoclimatic, and, at least partially, an anthropogenic feature.

Specific research works is planned for the future to analyse the more effective processes involved in this peculiar morphological evolution.

FIG. 13 - Detail of the weathering crust on the domelike hill of Cozzo Impiso. Part of the crust is uparched to form a small «bridge». Some minute parallel ridges alternated with hollows are developing in correspondence with the heads of the nearly vertical beds. The weathering crust is incongruent with the bedding and the solution is not able to enlarge the virtual cavities of the bedding planes (Cozzo Impiso) (photo by M. Macaluso).

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