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MORPHOLOGY AND MORPHOMETRY OF THE GRAN SASSO (CENTRAL ITALY) SURFACE KARST

ABSTRACT: LORÈ A., MAGALDI D. & TALLINI M., *Morphology and morphometry of the Gran Sasso (Central Italy) surface karst.* (IT ISSN 0391-9838, 2002).

Surface karst is believed to influence the qualitative and quantitative characteristics of the waters that feed aquifers. This paper focuses on the morphometry of some surface karst features and on their relations with groundwater resource conservation and management.

The study area is in the Gran Sasso karst massif of central Italy. It is a typical example of a Mediterranean hydrogeological system, consisting of Meso-Cenozoic carbonate and marly-silicoclastic sedimentary units that were involved in the Apennine thrust belt (lower Pliocene-upper Miocene). Since the upper Pliocene, extensional fault systems cut off the massif, leading to the formation of large tectonic basins (filled with Pleistocene continental deposits) and of areas with a typical basin-and-range morphology.

The karst process (probably occurring after the upper Pliocene) gave rise to both large-scale (karst plains and dolines) and medium-scale (karrenfelder) surface features.

Morphometry data on 141 karst plains, 382 dolines and 58 karrenfelder were collected by means of field surveys. The orientation and length of 682 macro-faults and 2,196 lineaments were recorded via aerial photos and geological maps. The study showed the occurrence of highly weathered red paleosols (Luvisol and Acrisol) as relict or buried soils of Pleistocene age, and of fairly differentiated soils of more recent age (Phaeozem). Statistical analyses indicated that the karst surface features are not fortuitous, but related to the tectonic fabric of the massif and to its geomorpho-pedological evolution.

The Gran Sasso karst landscape is similar to tropical karst landforms (conical towers), and with the small inselbergs and tors found in the crystalline rocks of the tropical belts of Africa and South America (mainly formed by chemical weathering). This may be due to the fact that the relief of Gran Sasso was modelled by chemical processes that began when the soil cover was thicker and very different from the soils of today. The deepening process of the karst surface forms is related mainly to water availability and, subordinately, to carbonate rock type and fracturing.

The morphological evolution of the dolines is controlled by the lithology, since their spatial enlargement in coarse-grained carbonate rocks is more significant than in mudstones.

The formation of karrens and pinnacles appears to be connected to the opening of individual joints. This finding suggests that the release of tensile forces after orogenetic stress is still active and that it may have been favoured by slope modelling and ice mass retreat in the last 10,000 years.

The collected data point to at least two karst stages, each with different surface features: high-altitude features may be attributed to present and recent karst activity, whereas low-elevation ones (inferred from selected buried and relict paleosols) are likely to have developed since the middle Pleistocene and to be scarcely active today.

KEY WORDS: Karst; Doline, Karrenfeld, Karst Plains, Graben, Central Italy.

RIASSUNTO: LORÈ A., MAGALDI D. & TALLINI M., *Morfologia e morfometria del carsismo superficiale del Massiccio del Gran Sasso (Italia centrale).* (IT ISSN 0391-9838, 2002).

Lo studio intende dare una descrizione quantitativa delle differenti fenomenologie del carso superficiale inserendole in un contesto idrogeologico di protezione e gestione delle riserve idriche sotterranee. L'area selezionata per tale studio è il massiccio calcareo del Gran Sasso (Italia centrale), sistema idrogeologico tipico dell'area centro-mediterranea. Il Gran Sasso è caratterizzato da sequenze carbonatiche e silico-calcareo-marnose meso-cenozoiche del dominio tetideo impilate tettonicamente nel Miocene superiore, durante l'orogenesi appenninica. Dal Pliocene superiore in poi l'edificio compressivo è stato ritagliato da faglie distensive responsabili della formazione di conche tettoniche colmate da depositi continentali quaternari e di morfologie tipo basin and range.

In questo particolare contesto si inserisce l'azione di dissoluzione carsica responsabile della formazione di morfologie sia alla macroscala (piani carsici e doline) che alla mesoscala (karrenfelder). Lo studio sul terreno ha portato all'acquisizione di dati morfometrici relativi a 141 campi carsici, 382 doline e 58 karrenfelder (tra cui sono stati misurati 898 solchi di dissoluzione). Inoltre, sono state misurate orientazione e lunghezza di 682 macrofaglie e 2196 lineazioni individuate da foto aeree e cartografia geologica.

I risultati ottenuti dall'analisi statistica evidenziano che le caratteristiche morfometriche del carso superficiale non sono casuali. Si possono invece inquadrare nel contesto geologico-strutturale e nell'evoluzione geomorfo-pedologica del massiccio.

La similitudine tra le forme del paesaggio carsico più diffuso nel Gran Sasso, quelle del carso tropicale (colline cupoliformi) e infine quelle a prevalente dissoluzione chimica delle rocce cristalline negli ambienti intertropicali dell'Africa e dell'America, fa ritenere probabile che la mag-

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gior parte dei processi di dissoluzione (specialmente alle quote più basse del Gran Sasso) sia avvenuta o avvenga sotto copertura pedologica, molto più spessa un tempo rispetto l'attuale e in alcuni casi, completamente differente. Infatti si osservano tracce di paleosuoli fortemente alterati di colore rosso (Luvisol e Acrisol) generalmente sepolti e suoli a profilo più differenziato e in genere ben conservati, presumibilmente pre-olocenici (Phaeozem).

Il processo d'approfondimento, come testimoniato dalle relazioni trovate per le varie forme carsiche superficiali, è strettamente legato alla disponibilità d'acqua e in via subordinata, alla fratturazione e alla tipologia delle rocce carbonatiche.

La litologia ha probabilmente influito sulle caratteristiche morfometriche delle doline poiché, a parità d'altre condizioni, il loro ampliamento tridimensionale sembra di preferenza avvenire in materiali carbonatici a grana più grossolana piuttosto che in quelli fango-sostenuti. Il processo di formazione dei karren e dei pinnacoli ad essi associati è legato all'apertura delle singole fratture e quindi suggerisce che il rilascio di tensioni latenti al termine degli sforzi orogenetici sia tuttora in atto, favorito forse dal modellamento dei versanti e dalla scomparsa delle masse ghiacciate a partire dagli ultimi 10 000 anni.

I dati raccolti evidenziano l'esistenza di almeno due fasi di carsismo con chiara distribuzione temporale e altimetrica, che si riflette sulle diverse morfologie carsiche di superficie. Le morfologie delle quote più elevate possono essere attribuite all'attività carsica recente e attuale, mentre il carsismo superficiale a bassa quota (sulla base dei paleosuoli ad esso collegati) si sarebbe sviluppato a partire dal Pleistocene medio e continuerebbe tuttora, sia pure con intensità sensibilmente più ridotta.

TERMINI CHIAVE: Carsismo, Doline, Karrenfelder, Campi carsici, Graben, Italia centrale.

INTRODUCTION

Surface karst is known to have a dramatic impact on the quantity and quality of water supplying fissured and karstified aquifers (Monjoie, 1975; Smith, 1993; Bakalowicz, 1995; European Commission, 1995). This paper reports the results from a research that was carried out as part of the Cluster C11b sub-project regarding karst groundwater resources conservation and management.

GEOLOGY AND GEOMORPHOLOGY

The Gran Sasso massif (Abruzzi) (fig. 1) consists of Meso-Cenozoic carbonate sequences. These sequences are made up of calcareous-dolomitic lithologies of the Latium-Abruzzi neritic platform *Auct.* and of calcareous-siliceous-marly lithologies belonging to basinal and slope lithofacies. The latter lithofacies originated from sedimentary environments adjacent to the Latium-Abruzzi platform (Accordi & *alii*, 1988). During the Apennine orogenesis, these units were thrust towards NE over foredeep turbidite units of upper Miocene age (Laga formation *Auct.*). Since the upper Pliocene, an extensional geo-

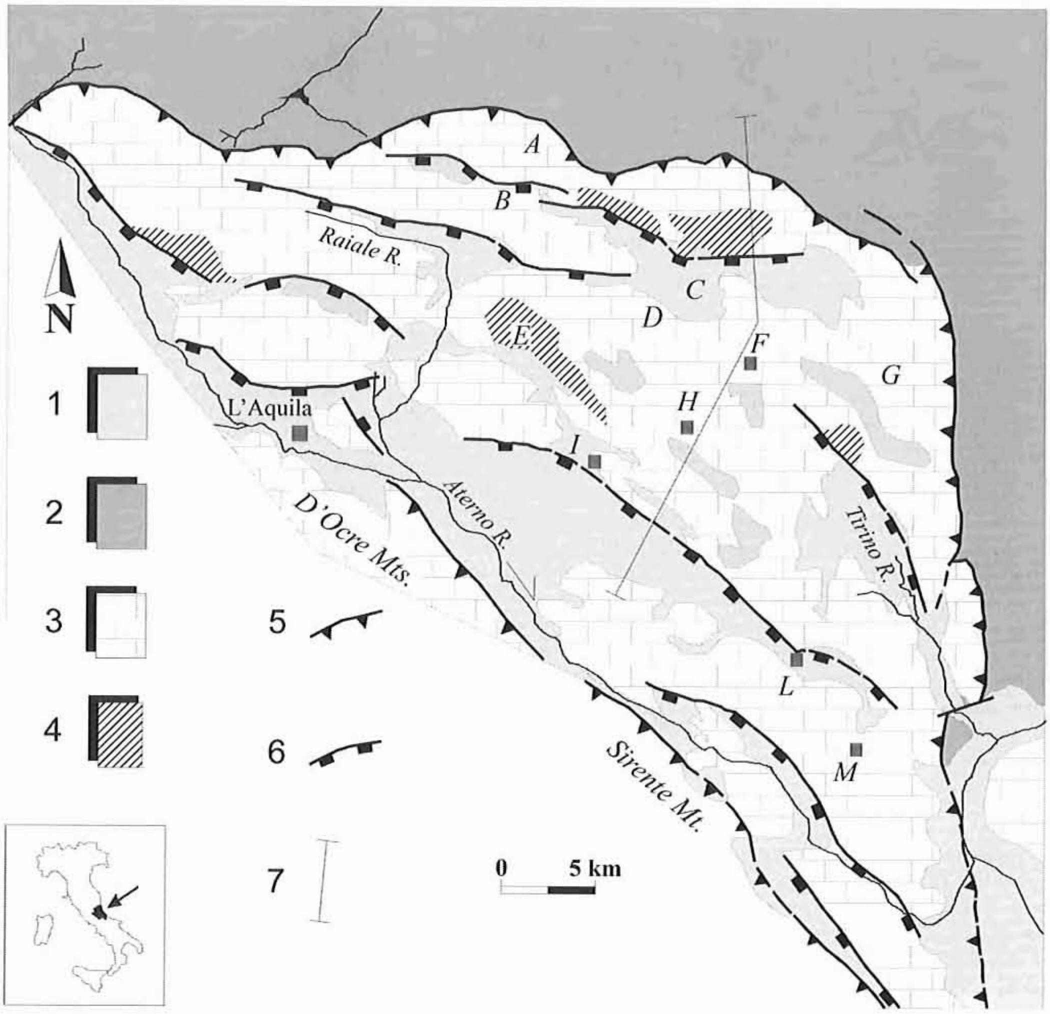


FIG. 1 - Geological map of Gran Sasso. 1 - continental deposits of tectono-karst basins (Quaternary); 2 - terrigenous deposits - pelites and sandstones - (upper Miocene.); 3 - carbonate sequences of platform (including shelf), scarp-basin and ramp facies (Miocene - upper Trias); 4 - basal dolomites (upper Trias); 5 - overthrust; 6 - extensional fault; 7 - profile of fig. 2.; A - Corno Grande; B - Campo Pericoli; C - Campo Imperatore; D - Piano Racollo; E - Monte Ruzza; F - Castel del Monte; G - Piano Voltigno; H - S. Stefano di Sessanio; I - Barisciano; L - Navelli; M - S. Benedetto in Perillis.

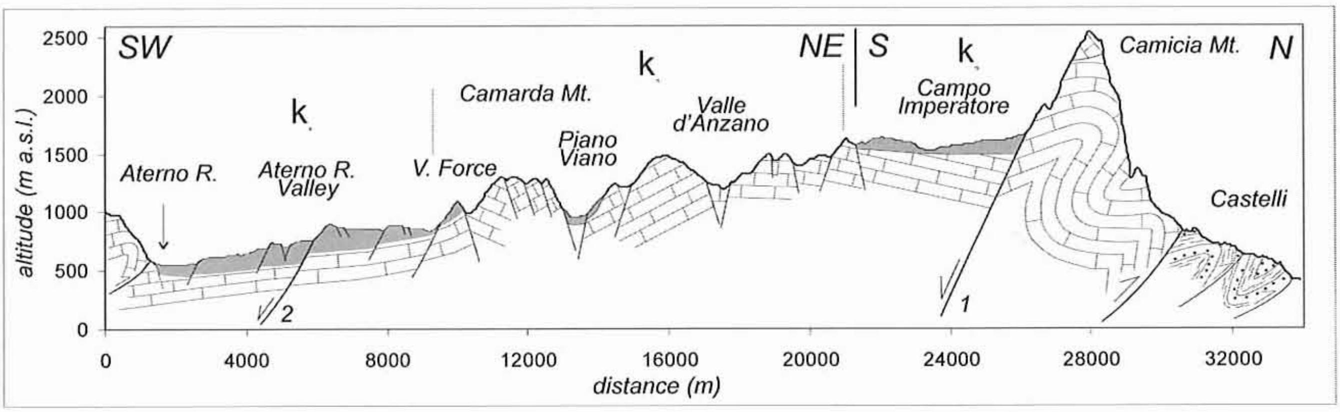
dynamic regime has generated NW-SE and E-W trending and SW dipping extensional faults (Vezzani & Ghisetti, 1998), as well as some intramontane basins (L'Aquila, Navelli and Campo Imperatore plains). These basins accommodated intense detrital sedimentation in lacustrine (e.g. the San Nicandro Formation), fluvial, slope and glacial (Campo Imperatore) environments (Bertini & Bosi, 1993; Cavinato & *alii*, 1994). Typical extensional fault systems are found at Castel del Monte. The systems are characterised by: i) «domino» geometries; ii) block rotation on horizontal axes; and iii) high rates of extension via the enucleating of high-angle fault systems dislocating and rotating previous fault systems (D'Agostino & *alii*, 1994). In the Quaternary, this structural setting favoured the formation of graben or semi-graben features. The grabens hosted the main karst landforms, giving rise to typical *basin-and-range* morphologies (fig. 2). The morphological trend transversal to the massif reflects the tectonic features of the different areas, as reported by D'Agostino & Tozzi (1997). To the north, the topographic high-elevation area is characterised by thrust faults and folds. On the back, the Campo Imperatore plain is related to the Plio-Quaternary activity of the extensional boundary fault (1, fig. 1). Southwestward, the *basin-and-range* relief is more indented and reflective of a horst-and-graben thin-skinned tectonic style. The karst landforms occur in the grabens of this area (e.g. Piano Viano, Valle d'Anzano). More southwestward there is the Aterno River valley, filled with Quaternary fluvio-lacustrine deposits. Its evolution was governed by another extensional fault (2, fig. 2).

Some of the extensional faults are still active and regarded as seismogenetic, as demonstrated by studies on present seismicity (De Luca & *alii*, 2000), palaeo-seismology and historical seismicity (Blumetti, 1995), as well as by in-well-measured active stress distribution (Montone & *alii*, 1999).

In the central Apennines, Gran Sasso is a well-defined unit, composed of a sequence of approximately NW-SE-trending morphological high and low features. The Aterno River borders it to the S and the Vomano River to the NW. To the NE, its boundary is less clearly defined and can be placed on the morphological boundary between the calcareous massif and the peri-Adriatic system of hills, which were modelled into Miocene and Pliocene marly-arenaceous sediments.

The inner part of Gran Sasso may be divided into two sectors, located NW and SE of a narrow belt, respectively roughly corresponding to the Corno Grande-Ruzza Mt. alignment.

In the first sector, the ridge consists of two alignments of peaks. The external one comprises the highest peaks of the massif (Corno Grande, 2912 m a.s.l.) and is carved by deep glacial valleys. The internal and less elevated ridge, forms continuous buttresses representing the head of the valleys and coinciding with the main watersheds.



doline type		soil	bedrock
k_1	"old"	Chromic Luvisol	calcareous conglomerate packstone
k_2	"poliphasic"	Calcaric Phaeozem	mudstone "fine-grained deposits"
k_3	"recent"	Rendzic Leptosol	mudstone with chert

FIG. 2 - Schematic geological profile showing the main soils and types of dolines (k_1, k_2, k_3). The shaded area shows the Quaternary deposits filling the tectonic depressions (Campo Imperatore and Aterno River valley; the brickwork area shows the Meso-Cenozoic rocks representing the backbone of the reliefs. Numbers 1 and 2 identify the 1st order extensional faults that affected the evolution of the main tectono-karst basins.

The latter alignment is bounded towards SW by a steep fault slope 1000 m high. The slope separates the alignment from a wide horst-and-graben area (mean elevation 900-1300 m a.s.l.), whose margins are cut by deep fluvial valleys.

The wide tectonic depression of L'Aquila (mean elevation 600-800 m a.s.l.), filled with Pleistocene lacustrine and fluvial sediments, which hosts the Aterno River valley, is located towards the SW.

By contrast, in the south-eastern sector, the ridge has a single alignment of peaks, bounded to the NE and SW by steep slopes. The north-eastern slope, 1000-1300 m-high, always steep and, in places, sub-vertical, and rising above the hills of the Adriatic foreland, is an impressive feature of the landscape.

Towards the SW, the ridge is connected to the wide tectonic depression of Campo Imperatore (mean elevation 1500-2100 m a.s.l.), filled with a thick Pleistocene and Holocene sedimentary sequence.

The depression is followed by a wide horst-and-graben area (mean elevation 1,000-1,600 m a.s.l.) with numerous endorheic tectono-karst basins. In this area, Bertini & *alii*, 1989, reported the occurrence of a high-elevation land surface (Anzano surface). This surface, with moderate relief, is preserved in small limbs or alignments of peaks and watersheds, split by several tectono-karst basins. Bosi & Messina (1992) interpreted this surface as an erosional surface of upper Pliocene age.

Proceeding south-westwards, the following features are observed: i) tectonic depression of Navelli-Barisciano (mean elevation 700-1000 m a.s.l.), filled with dominantly lacustrine sediments of lower-middle Pleistocene age; ii) a set of low horst-and-graben relief forms (mean elevation 800-1300 m a.s.l.), cut by deep fluvial valleys; iii) the Aterno River valley, deeply entrenched and, in places, in the form of a gorge.

Tectonic activity in the Pleistocene significantly influenced the morphology of the massif, creating numerous inter-montane depressions. The major ones were filled with thick continental sedimentary sequences. The minor ones often evolved into endorheic basins, partially remoulded by karst processes and often supporting lacustrine or palustrine environments (some of them retaining small lakes).

In the upper Pleistocene, the most elevated portions of Gran Sasso experienced intense glacial remodelling, with the formation of deep valleys and the erosion of existing morphologies.

Fluvial morphogenesis affected the massif to a limited extent as it became dominant only at its margins, where some tectono-karst basins are deeply cut by valleys. At present, the massif has no significant streams, the few perennial ones running at its margins.

Starting from the upper Pliocene most of the areas have been subjected to chemical weathering that resulted in karst landforms. This action has been favoured by the distinctive geological-structural setting of the area, as well as by its past and present morphology and climate.

TECHNICAL CHARACTERISTICS OF THE KARSTIFIED ROCKS

Karst-affected lithotypes are marly limestones, massive limestones, and calcarenites of Meso-Cenozoic age. These rocks have the following geotechnical properties:
- cohesion between joints = 0.03-0.05 MPa;
- compressive strength = 35-50 MPa;
- tensile strength = 1-3 MPa;
- Hoek's Geological Strength Index (GSI) = 30-80;
- angle of friction: 30°-37° for massive limestones, 20°-30° for all other ones.

According to Duhnam's classification (in Bosellini & *alii*, 1989), these rocks include mudstones, packstones, rudstones and boundstones. Their mean density is assumed to be equal to 2,720 kg/m^3 (Capuano & *alii*, 1998).

Pleistocene conglomerates and calcareous breccias are less common but equally susceptible to solution processes.

SLOPE MODELLING

The Gran Sasso landscape may be generally defined as «tectono-karst» (Sauro, 1986). However, three parts with different morphologies can be distinguished:

i) a high part, whose elevation exceeds 2000 m, consisting of the sub-vertical walls of the highest peaks of Gran Sasso, of glacial valleys and of scarps;

ii) an intermediate part, consisting of dome-shaped calcareous reliefs (domed or polygonal karst), separated by dry valleys and karst basins;

iii) a basal part, with convex but irregular hills, karst basins and large dolines.

Convex and domed slopes were reported by Derruau (1972) in the French «Craie», where they form «convex humps» resulting from the isotropic response of the rock to both chemical weathering and creep which act on the detrital-pedogenetic material. More recently, Trudgill (1985) reviewed the various models proposed for slope modelling in various parts of the world, stressing the importance of the soil cover as a source of CO_2 and, thus of acidity. Soil cover is also assumed to regulate the flow of seepage, evapotranspiration and surface and sub-surface runoff waters. Consequently, carbonate rocks with moderate anisotropic response may generate slopes that, from top to bottom, tend to be convex, rectilinear and concave, respectively. Given the particular morphology of the investigated area, processes of this type may have operated on the intermediate- and low-elevation parts of the massif. The following considerations, taking a more in-depth approach to the morphogenesis of the massif, support this assumption. Therefore, the domed calcareous hills are highly reminiscent of tropical hills, although their slopes are gentler. Also the shapes of some calcareous «pinnacles» of Gran Sasso and of the nearby d'Ocre mountains are not very different from the English tors (fig. 3). Even if different geomorphic processes often give rise to very similar forms, and knowing the genesis of tropical relief, the

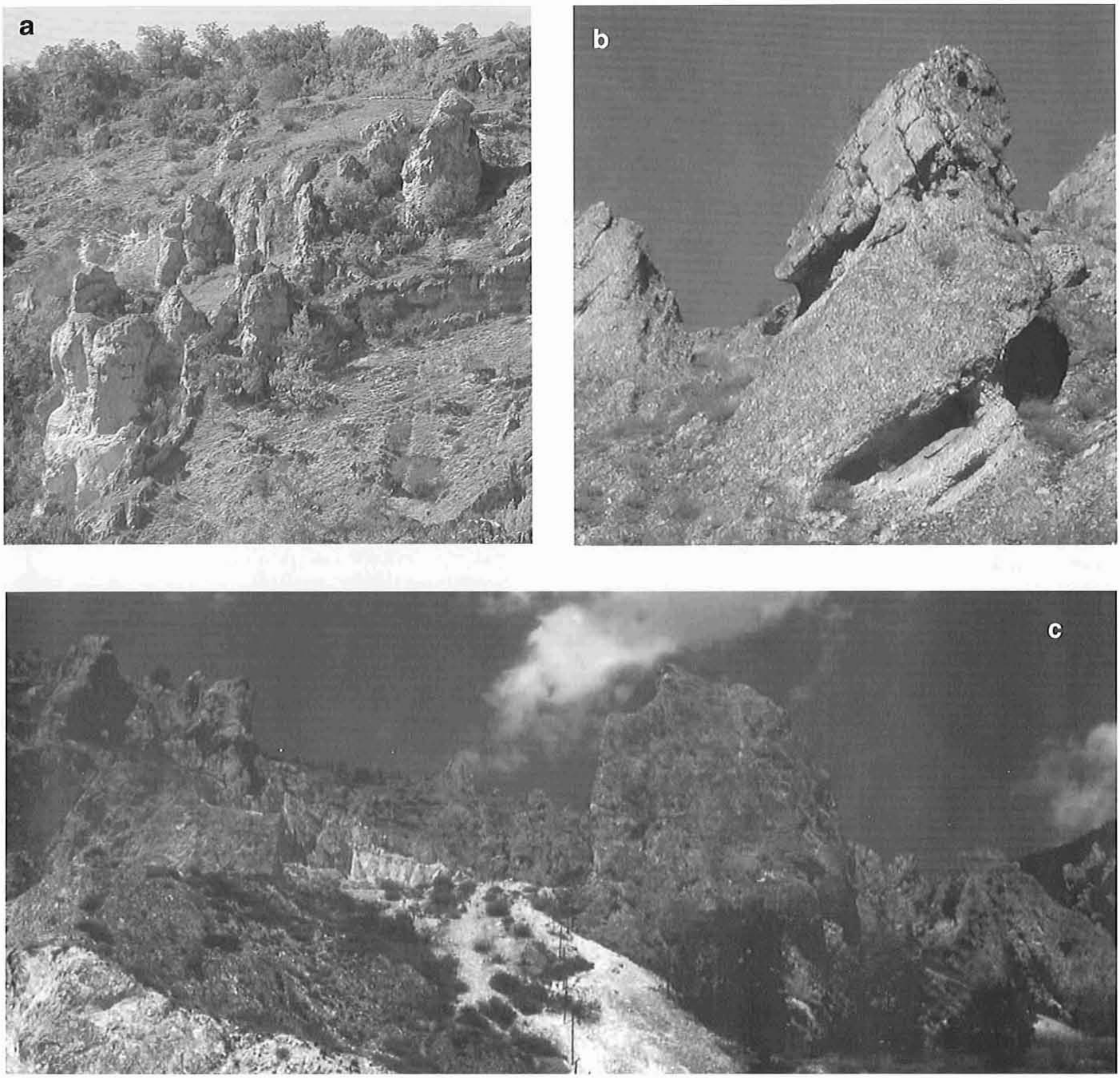


FIG. 3 - (a) «Pinnacles» in the upper Raiale stream valley, modelled into Mesozoic limestones (height: about 15 m). (b) «Pinnacle» in the middle Raiale stream valley, modelled into Pleistocene calcareous breccias (height: about 8 m); note the approx. 40° - dipping bedding. (c) «Pinnacles» at Roccapreturo (S. Benedetto in Perillis), modelled into Mesozoic limestones (height: 20-30 m).

Gran Sasso slope modelling is likely to have been highly conditioned by chemical processes occurring under soil cover. This argument is supported by the study of the relationship between karst basins, lithotypes and soils. In effect, the most common low-elevation karst basins are associated with polyphase paleosols, now almost disappeared, of the Luvisol and perhaps Acrisol type (FAO-UNESCO, 1998). These paleosols may have developed on coarse-grained limestones, such as the lower Pleistocene breccias of Fonte Vedice (Bosi & Messina, 1992) («mortadella breccias»: Demangeot, 1965). Few Luvisols (soils with clayey B-horizon corresponding to the Alfisols of the USDA classification) are to be considered as relict. Conversely, more weathered Luvisols (*Munsell Soil Colour* 5 YR-7.5 YR) are generally buried under detrital material of variable age from the upper Pleistocene to the Holocene and occur as 50-100 cm thick intercalations. It is worth emphasising that the «pinnacles» are often veneered with Fe hydroxides and clays whose colours are very similar to those of the above-mentioned paleosols.

By contrast, the less well developed dolines and karst valleys, as well as the dome shaped hills, which are frequently carved out of the fine-grained limestones (mudstones), are associated with soils of more recent age (Holocene-upper Pleistocene): Calcaric Phaeozem, Calcaric Cambisol and Rendzic Leptosol type (Magaldi & Tallini, 2002).

Therefore, the intermediate and basal parts of the massif are likely to have been modelled predominantly by chemical weathering beneath a soil cover thicker than the present one, and to have evolved in multiple and different climatic stages. Chemical weathering was combined with gelifraction, creep, surface runoff, gelifluxion and mass movements, which periodically removed the soil cover, as observed in the stratigraphic sequences of the L'Aquila plain and in some test holes dug into the largest dolines.

No reliable data are available on the rate of chemical erosion, which was responsible for slope modelling. Nevertheless, it must have been variable over the past 10,000 years and, almost certainly, at different elevations of the massif. However, from some relations proposed for temperate countries (Ford & Williams, 1989) and for Italy (Pulina & Sauro, 1993), and direct measurements of emerging cherty nodules of the limestones, a solution rate of 11-90 mm/1,000 years was assumed, i.e. an order of magnitude of $10\text{-}10^2$ mm/1,000 years. This preliminary assumption is consistent with the value of 81 mm/year reported for the Gran Sasso area by Demangeot (1967), and with the likely value of the present solution rate due to CO_2,-rich waters, according to the formula proposed by Atkinson & Smith (1976):

Erosion rate (mm/1,000 years) = (P-E) * H / γ = 16

where P - E is the water surplus (about 500 mm/year), H is the mean hardness of the most representative springs of the Gran Sasso karst aquifer in mg/L (90) and is the carbonate rock density (2,720 kg/m^3).

KARST PLAINS (CAMPI CARSICI)

The following parameters of 141 karst plains (campi carsici) lying at an elevation of 750-1900 m a.s.l. were measured.

Morphometric data:
- max. diameter;
- min. diameter;
- direction of max. diameter;
- bottom sense (azimuth of the vector linking the highest point of the perimeter to the lowest point of the floor);
- perimeter sense (azimuth of the vector linking the highest point and the lowest point of the perimeter);
- base level;
- max. depth;
- min. depth;
- height of closing threshold;
- min. slope gradient of edges;
- max. slope gradient of edges;
- surface area.

Hydrological data:
- surface area of karst plain drainage basin (Sp) which is the surface area of the drainage basin directly pertaining to the karst landform, net of the surface area of the tributary karst plains;
- total surface area of the drainage basin (St);
- effluents, if any;
- Strahler's order of internal hydrography;
- swallow-holes, if any;
- evidence of perched aquifer;
- order of affluent hydrography, if any;

For characterising and expressing the geometry of karst landforms, the flatness index, used to describe the shape of pebbles (Pettijhon, 1975), was applied. This is according to the well-known relation:

$$(a+b) / 2c$$

where a>b>c are the three main diameters of the pebble and, in our case, the max. diameter, the min. diameter and the max. depth of the karst landforms.

Interesting relations were identified between the measured parameters. The most evident relation connects mean diameter to depth (fig. 4), demonstrating the isotropy that governs the formation of cavities and karst conduits. A very marked relation links flatness, surface area of karst plain drainage basin (Sp) and depth of karst plains. The inverse proportionality relation between the flatness/drainage basin surface area ratio and karst plain depth (fig. 5) clearly indicates that, area of the drainage basin being equal, the sum of the main dimensions of the karst plains is constant. This fact may be interpreted as the effect of a solution process which worked with the same intensity and style in all the karst valleys, albeit conditioned by structural features. Moreover, there is a direct relation between the surface area of the karst plains drainage basin and the karst plain surface area. The determination coefficient is 0.64.

These results show that the process of development of the karst plains was the same and worked isotropically beginning with the «depressions» controlled by the Plio-Quaternary extensional tectonics.

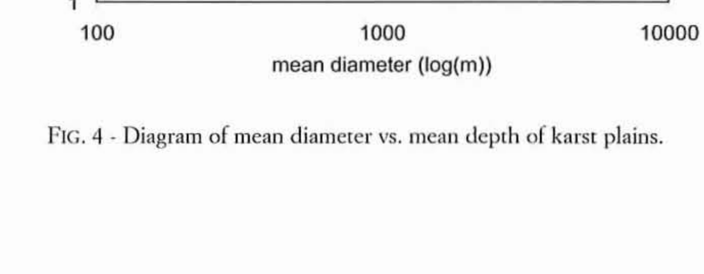


FIG. 4 - Diagram of mean diameter vs. mean depth of karst plains.

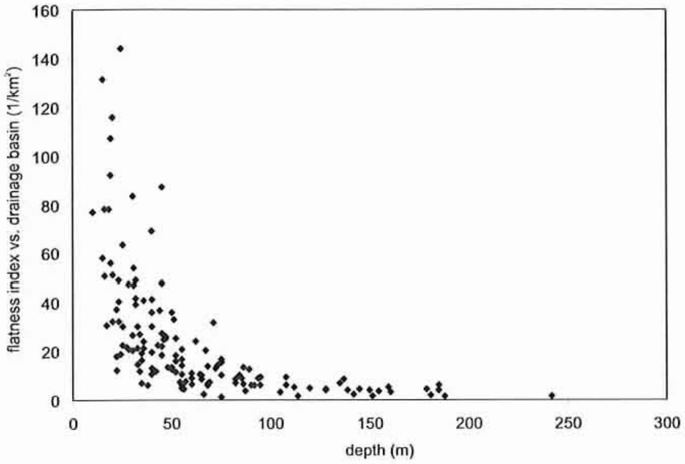


FIG. 5 - Diagram showing the relation between the flatness index vs. the drainage basin surface area and the depth of karst basins.

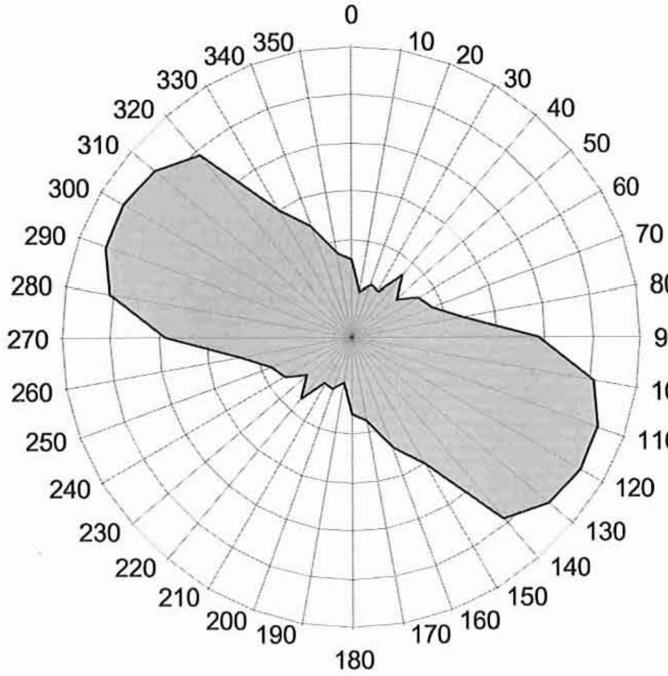


FIG. 7 - Linear length vs. direction of lineaments.

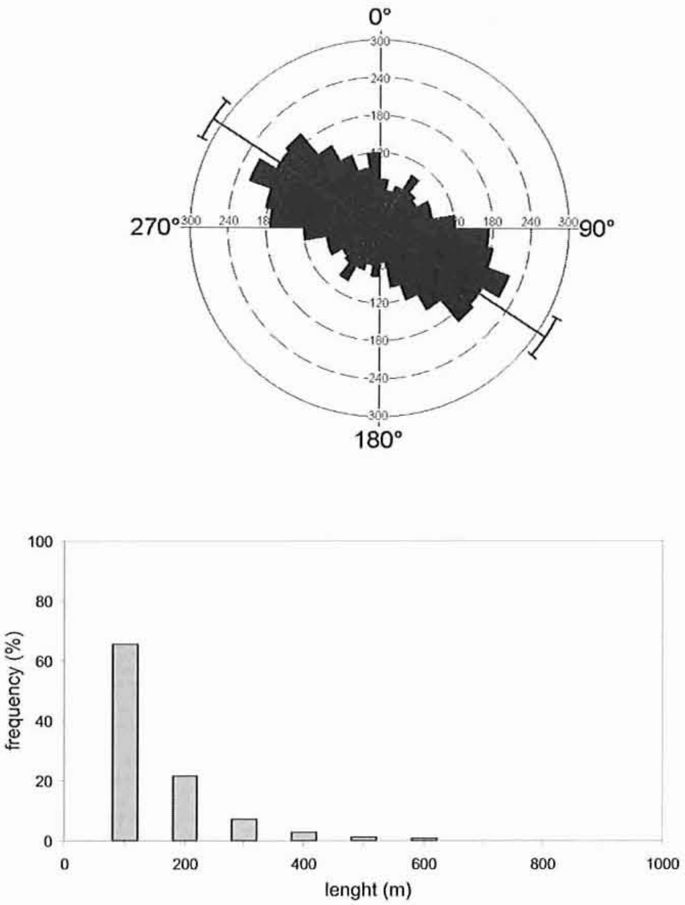


FIG. 6 - Rose diagram and frequency histogram for the length of the lineaments identified at the edges of the karst basins (total data = 2196).

The orientation of 2196 lineaments (fig. 6), corresponding to the edges of the karst plains, was also measured on aerial photographs (1:33,000 scale). By comparing the orientation of the lineaments with their linear extension (fig. 7) it is evident that the dominant trend is N 100° and N 150°, averaging N 123°. These findings are closely related to extensional faults, as demonstrated by the rose diagram of fig. 7. The histogram for fault-length (fig. 8) indicates the faults are less than 4 km-long, whereas the same histogram for lineaments shows that over 95% of them are less than 400 m-long (fig. 6). Therefore the macro-faults are NW-SE-oriented features, along which the karst plains are distributed. Moreover, most of the Gran Sasso karst plains are NW-SE- and, to a lesser extent, EW-elongated. They can thus be defined as karst basins of a structural type (CVIJIC, 1960) emplaced in graben or semi-graben structures of Quaternary age (fig. 9).

DOLINES

Dolines are scattered over almost the entire massif at elevations of 550 to 2300 m a.s.l.

Most of the observed forms are typical solution dolines, whose walls were modelled into the rock and whose floor was generally filled with a more or less thick layer of sediment. The dominant features are of the «bowl» and «dish» type. Their size ranges from a few meters to some hundreds of meters. Fossa di Pietrarossa, located roughly 2.5 km SE of S. Benedetto in Perillis, is the only identified collapse doline. This doline is shaped like a pothole with 120 m max. diameter and 75 m max. depth.

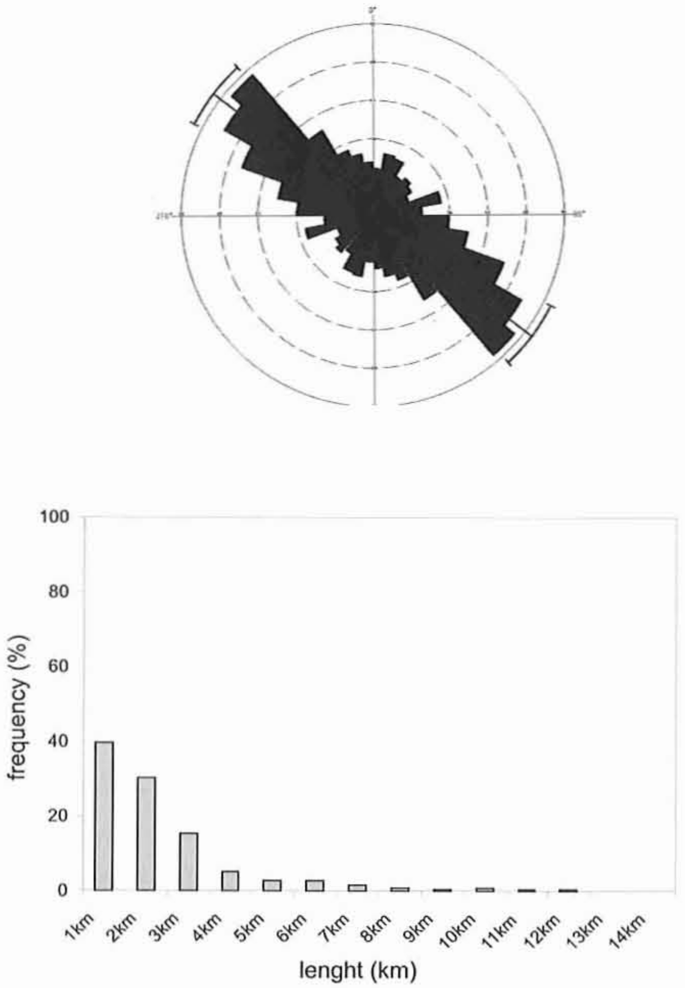


FIG. 8 - Length of the extensional macro-faults identified in the Gran Sasso (total data = 632): rose diagram and frequency histogram.

Small-sized dolines with signs of sinking were observed at Campo Pericoli and N of Castel del Monte.

Considering the size and location of the observed dolines, three groups can be distinguished:

1. Large-sized dolines (mean max. diameter: 150 m) in the Aterno River valley; always isolated, they are modelled into the calcareous conglomerate, breccia and silt of lacustrine and/or fluvial environments which fill the valley or in the limestones making up the slopes that bound it.
2. Medium-sized dolines (mean diameter of 30 to 200 m). These are located in the area extending between the ridge and the tectonic depressions of L'Aquila-Scoppito and Navelli-Barisciano, and on the relief lying between the latter ridge and the Aterno river valley. They are usually arranged as *spot dolines* and, more rarely, as polygonal karst dolines (Bolza Mt. - fig. 12, Colle Fossa Palomba near Navelli). They lie in areas that are identifiable as limbs of an ancient erosion surface (Anzano surface) or however with low relief energy; sometimes they are isolated on peaks or relief, which are intercalated with tectono-karst basins.
3. Small-sized dolines (mean min. diameter: 30 m). They are found in three typical settings: i) on the bottom of glacial cirques and valleys, as *spot dolines* modelled into the bedrock limestones; ii) inside tectono-karst basins, modelled into filling sediments, as *spot dolines* and/or «connected dolines»; iii) inside medium-sized dolines, isolated or in groups of 2-3, modelled into the floor filling sediments.

For each of the 382 dolines considered, the following parameters were measured according to the classification proposed by Bondesan & *alii* (1979):

- max. diameter (m);
- min. diameter (m);
- direction D_{max} (degrees);
- *bottom sense* (degrees);
- *perimeter sense* (degrees);
- base level (m a.s.l.);
- max. depth (m);
- min. depth (m);
- min. slope gradient of edges (degrees);
- max. slope gradient of edges (degrees);

The doline fills were also described and analysed.

The results of the above analyses enabled us to single out significant relationships between the mean diameter of the dolines, their mean depth, their elevation and the bedrock lithology.

Mean diameter and mean depth of the dolines are directly proportional (fig. 10). The resulting distribution is also related to elevation and lithology (fig. 11). The width of the dolines, larger at low elevation and smaller at higher elevation, is presumably due to the age of the karst process and to differences in climatic conditions. The three easily

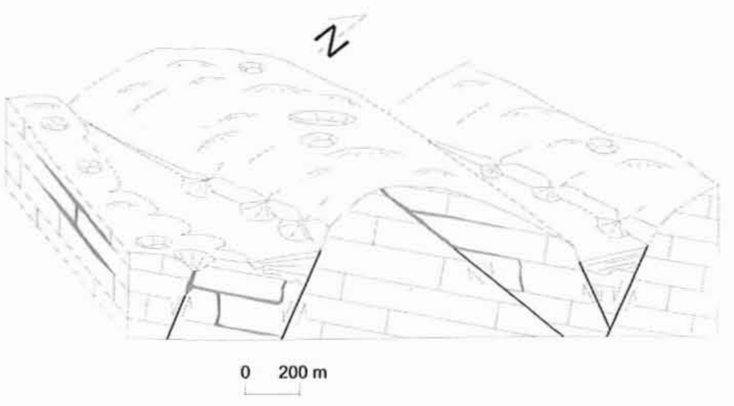


FIG. 9 - Block diagram showing the close relationship between the location of karst basins and the Quaternary grabens of Gran Sasso.

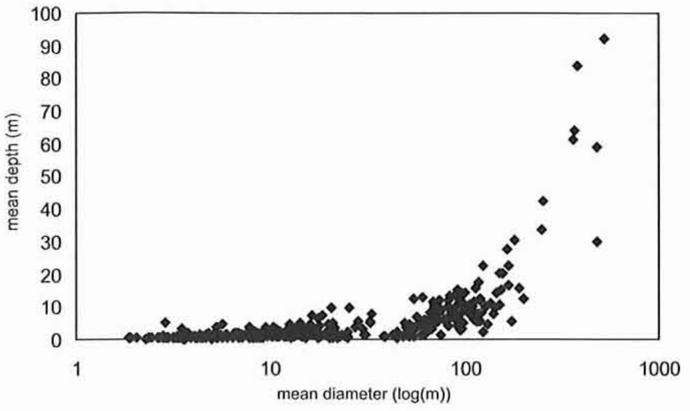


FIG. 10 - Diagram of mean diameter vs. mean depth of the Gran Sasso dolines.

distinguishable groups of dolines have different lithology. The first group, concentrated at elevations of 2000 to 2500 m a.s.l., occurs on chert-bearing mudstones. The second, occurring between 1700 to 1000 m a.s.l., occurs in a more heterogeneous lithologic complex, including mudstones, grainstones and subordinate wackestones, packstones and rudstones, as well as «terrain» (soil , soil sediments, colluvia). The third group developed on limestones, which are coarser than the above-mentioned ones, such as breccias, calcareous conglomerates and packstones, and generally occur below 1000 m a.s.l.

With regard to the sequence of the main lithotypes (fig. 2), the doline morphology points to at least three families (k_1, k_2, k_3), belonging to at least two karst stages: older age karst for the most part well-developed at a lower elevation, with no soil cover (k_1); younger karst for the one at a higher elevation (k_3). There is also an intermediate family including both older and younger dolines (k_2).

There are about 20 dolines in group k_1, whose soils show more developed pedogenesis (Chromic Luvisol); their size is larger than all the other ones (with volumes exceeding 300,000 m^3 on average). They lie within the middle Aterno River valley or on the calcareous buttresses of the Ocre Mountains, just outside the study area between 600 and 1200 m a.s.l.

The younger dolines of group k_2 (fig. 2) occur in the deposits that filled the karst basins (Racollo flat, Voltigno), i.e. inside larger dolines; this fact suggests that the present karst morphology exploited the existing pathways of water discharge.

More detailed analysis of the surface area of 99 larger dolines (all groups), by digitising the polygons making up their perimeter reveals the surface areas are correlated with the surface area of the corresponding drainage basins (fig. 12) according to a relation similar to the one found for the karst plains.

KARRENFELDER (ASSEMBLAGES OF KARRENS)

Karrenfelder are a common occurrence in the massif, at elevations of 400 to 2,200 m a.s.l.. They are easily discernible on steep slopes at a relatively low elevation. Here, the individual karren often bound «pinnacles» and *clint blocks*. These karrens are similar to those observed on rocks of a different lithology, under climatic conditions ranging from periglacial to tropical and subtropical. We can distinguish:

i) Karrenfelder whose individual karrens are controlled by joints (*Kluftkarren*), usually occurring at medium and high elevation;

ii) Karrenfelder with rounded hollows (*Rundkarren*), which are typical of lower elevations and are often associated with «pinnacles».

Fifty eight Karrenfelder and a total of 898 solution furrows were examined and the following parameters measured (Perna & Sauro, 1978):

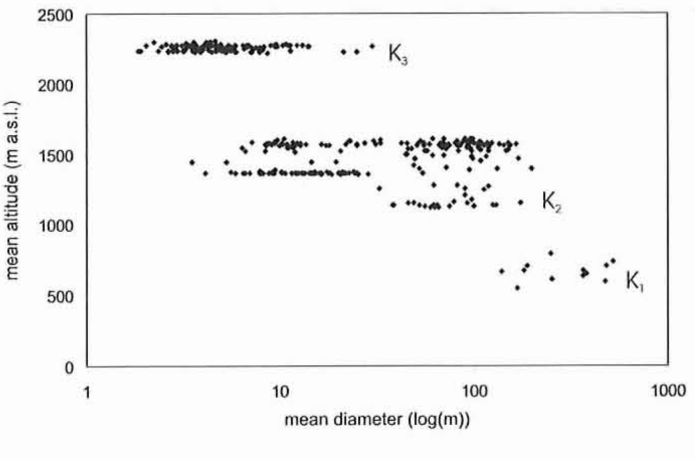


FIG. 11 - Diagram of elevation vs. mean diameter of the Gran Sasso dolines.

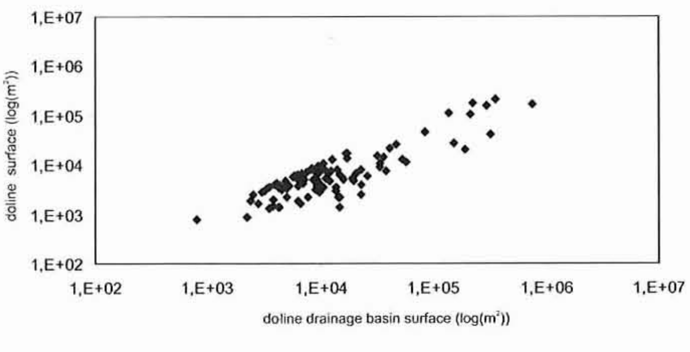


FIG. 12 - Diagram of doline surface area vs. doline drainage basin surface area.

- strike and dip and inclination of the plane tangent to the topographic surface;
- strike and dip of the axial plane of the individual karren;
- max. and min. gap of their opening;
- field measurable length of their opening;
- field measurable max. depth;
- materials filling their opening.

In the Karrenfelder measuring stations or in their immediate vicinity, 55 structural measuring sites were also set up, where the following parameters of 1107 joints were recorded:

- type of joint;
- strike and dip of axial plane;
- mean spacing;
- lithology and Geological Strength Index (GSI) according to HOEK (2000).

The angular directions of karren and joints clearly reveal the randomness of the two orientations and thus their similarity, although some directions seem to dominate.

The second relation (fig. 13) deals with the max. and min. opening of the karren limbs, measured in the field along the part that was visible.

The relationship is linear, $r^2 = 0.70$ with probability = 95%. This result is of paramount importance, as it may prove that the formation of the karrens not only depends on chemical solution, but also on concurrent dilatation of the two limbs of the joint, according to the well-known «crocodile» mechanism (Erisman & Abele, 2001). Hence, the karst process is likely to have taken place preferably in sites where, all other conditions being equal, the rocks tended to have more or less planar joints, resulting from residual stress release upon geodynamic tensional states. This is supported by the fact that the orientation of the joints measured inside the Gran Sasso highway tunnel is similar to that of surface joints. However, the former are sealed and have no evidence of karst solution processes on their surfaces, in spite of water dripping. Furthermore, most of the Karrenfelder are concentrated (with a quasi-gaussian distribution) at elevations of 1200 to 1600 m, in

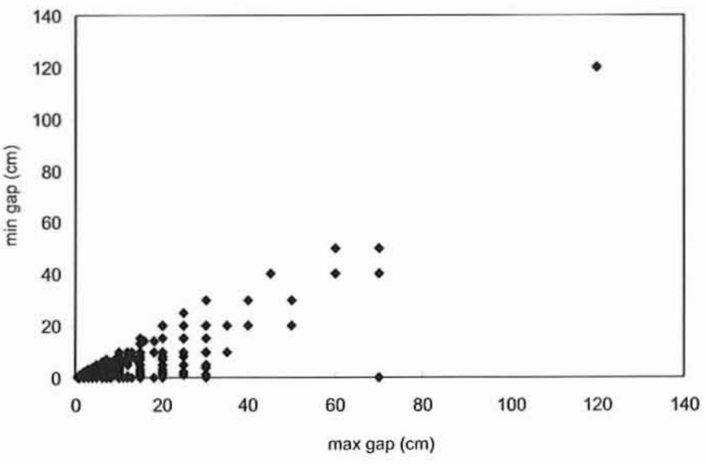


FIG. 13 - Diagram of max. vs. min. gap of the measured karren.

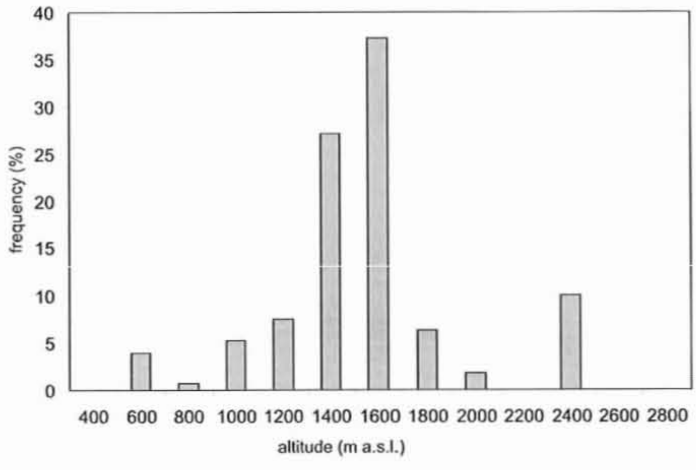


FIG. 14 - Frequency histogram of karren vs. altitude.

one of the most fractured and faulted areas. In the two «tails» of the distribution, the phenomenon is negligible. The distribution may be also interpreted as the result of the interference of karst morphogenesis with other processes. Above 1600 m a.s.l., the frost weathering tends to inhibit the formation of karrens; at lower altitudes, the same mechanisms that led to the formation of the «pinnacles» (all lying below 1300 m) may have obliterated the Karrenfelder (fig. 14).

Another significant finding concerns the areal distribution of the Karrenfelder. This morphotype scarcely occurs in the area extending between Campo Imperatore and the village of S. Stefano di Sessanio, and it is rare in the area between the Raiale stream valley and the L'Aquila plain. By contrast, it is fairly common at the south-eastern and south-western margins of the massif. These latter areas must have been subjected to stress and its release deriving from the formation of large tectonic depressions of the Tirino R. valley, Navelli plateau and Aterno R. valley.

Finally, it should be pointed out that the Karrenfelder are often forms confined to the small surfaces at the top of the relief or along watersheds, in a landscape that would otherwise have no record of active surface karst corrosion. The formation of the karrens by an extensional activity, is a speculative assumption, which is to be validated by more detailed studies, even considering the present tectonic regime. Indeed, some families of karrens might open up as a result of normal faults.

CONCLUSIONS

Once again, it is evident that the morphometry of surface karst is not fortuitous, but is part of a unique geological-structural, lithological and geomorpho-pedological setting.

The similarity between the most common karst landforms of Gran Sasso, those of the tropical karst (domed

TABLE 1 - Main characteristics of the two types of karst identified in Gran Sasso

	Old Karst (k_1)	Recent & Actual Karst (k_2 & k_3)
Shape of Karrenfelder	Rill- karrens smoothly edged, cutting reddish soils (Hue 7.5 & 5 YR), related to along hill slopes dolines and hypogeal conduits	Fractures limited, sharply edged, cutting brown soils (Hue 10 YR)
Clay and iron oxides coatings	Frequent	Very scarce if any
Lithology	Calcareous conglomerates and Packstone	Mainly Mudstone
Fractures occurrence	Moderate	High
Slope morphology	Domed, scarcely stepped slopes, occurring near tectonic- karstic basins	Irregular and straight slopes
Along hillslope collapse dolines	Frequent	Any
Pinnacles	Frequent	Any
Hypogeal conduits	Phreatic channels and fractures	Irregular fractures
Related soils	Chromic and Haplic Luvisol	Rendzic Leptsol & Calcaric Phaeozem
Altitude range	500-1000 m	1000-2500 m

hills) and those mainly due to chemical weathering of crystalline rocks in the intertropical environments of Africa and America, suggests that most of the Gran Sasso solution processes, especially at the lowest elevations, occur or have occurred, beneath the soil cover. In the past, this cover must have been much thicker and, in some cases, very different from the soil cover that exists today.

As demonstrated by the relationships identified for the karst plains, the deepening is closely connected to water supply and, subordinately, to fracturing and types of carbonate rock. Fracturing generally operated on a small scale, guiding the enlargement of the joints and the development of surface karst according to specific tectonic trends. On a large scale, it significantly reduced the original anisotropy of the rock materials, thereby favouring isotropic solution processes, as in the case of tropical crystalline rocks. Lithology probably affected the morphometry of the dolines. All other conditions remaining equal, the tridimensional enlargement of the dolines seems to have preferably occurred in more coarse-grained materials (calcareous conglomerates and breccias, packstones, grainstones, rudstones) rather than in fine-grained ones (mudstones with and without chert lenses). Another finding concerns the genesis of the Karrenfelder and of «pinnacles». The relation of fig. 13 indicates that the process is generalised to all the joints. This fact suggests that orogenetic stress release is still under way and is likely to have been eased by slope modelling and ice retreat in the last 10,000 years. With regard to the «pinnacles», research conducted on highly lithoclased rocks in southern England (Lewis, 1996), stresses the importance of both chemical action in aggressive pedoclimatic environments and physical action under periglacial conditions.

The data collected clearly show the occurrence of at least two karstic stages, reflecting different morphologies and altitudes of surface karst (table 1). Only the morphometry of the dolines infers the occurrence of an intermediate stage. The karst landforms lying at the highest elevations (Campo Pericoli) have a morphology similar to the ones located immediately below them. The difference appears to be local due to different types of soil and different microclimatic conditions and can be ascribed to the recent and present karst. At these elevations and in more ancient times, karst processes were very different from the present, owing to local adverse weather conditions. Conversely, the low-altitude surface karst is different. It is based on paleosols, which have developed since middle Pleistocene times (Magaldi & Tallini, 2000) under conditions that still continue today, albeit with a much lower intensity.

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