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ASSESSING RELATIONSHIP BETWEEN SURFACE KARST FEATURES AND SOME GEOSTRUCTURAL ELEMENTS BY GIS IN THE GRAN SASSO RANGE (ABRUZZI, ITALY)

ABSTRACT: MAGALDI D., LORÈ A. & PERONI P., *Assessing relationship between surface karst features and some geostructural elements by GIS in the Gran Sasso range (Abruzzi, Italy)*. (IT ISSN 1724-4757, 2004).

Several studies carried out previously on the Gran Sasso Range and nearby (Monti della Laga) in Province of L'Aquila (Abruzzi, Italy) noted qualitative relationships among the rock fracturing degree, and the karst landforms. This research deals with the identification of more detailed relationship between some geo-structural and morphologic elements and karst features.

The rock fracturing conditions of carbonate formations are like to increase the karst processes by the forming of preferential way for penetrating waters. A comparison between jointing class and surface karst landform was carried out using a standard GIS approach (ILWIS).

The results showed a significant inverse correlation between jointing density classes and the karst polygonal features. Moreover by combining the geostructural information with the karst landform occurrence, the AA. conclude that: the faults occurrence and proximity are like to increase both the jointing density and the fissure permeability of the carbonate rocks; the high degree of rock jointing is favouring a rapid water penetration so hindering more complex karst landform genesis. Some petrographic observations suggest that the hard limestone are showing more micro-stress features than softer ones.

KEY WORDS: Karst, Rock Discontinuities, Geographic Information System, Micro-tectonics, Gran Sasso (Italy).

RIASSUNTO: MAGALDI D., LORÈ A. & PERONI P., *Uso del GIS per il riconoscimento delle relazioni tra carsismo superficiale ed alcuni elementi geostrutturali nelle formazioni carbonatiche del Massiccio del Gran Sasso*. (IT ISSN 1724-4757, 2004).

Una serie di indagini geomorfologiche e geologiche iniziate alcuni anni fa sul massiccio carsico del Gran Sasso e nelle immediate vicinanze (Monti della Laga) in Provincia di L'Aquila avevano identificato sia pure in via preliminare una relazione tra forme carsiche superficiali e grado di fratturazione degli ammassi rocciosi. Questa ricerca, condotta nella precedente area campione è stata svolta sulle relazioni delle varie forme carsiche isolate e poligonali riconosciute in campagna (campi di doline, doline singole, polja, uvala, doline isolate, pinnacoli, inghiottitoi, karren) con il grado di fratturazione a livello regionale degli ammassi rocciosi carbonatici e con alcune figure microscopiche dei litotipi calcarei attribuite comunemente ad effetto di stress tettonico e/o litostatico.

È noto che il grado della fratturazione delle rocce carbonatiche determina la facilità secondo la quale le acque superficiali possono penetrare nella roccia provocando così il fenomeno carsico. Allo scopo di effettuare un confronto quantitativo tra la distribuzione delle classi di fratturazione delle rocce e quelle di densità carsica superficiale, si è utilizzata la tecnologia dei sistemi informativi geografici tramite il pacchetto ILWIS.

I risultati hanno mostrato che quasi tutte le formazioni carbonatiche del Massiccio rivelano un grado di fratturazione da moderatamente alto ad alto e che esiste una significativa correlazione inversa tra forme carsiche poligonali e grado di fratturazione. Questo fatto significa che dove la fratturazione della roccia è più intensa, l'infiltrazione delle acque è più veloce ma il fenomeno carsico è maggiormente rallentato con produzione di una maggior quantità di forme complesse. Una interessante relazione si trova ancora tra la densità delle forme carsiche e la loro distanza da faglie e fratture: infatti la maggiore distanza dalle strutture tettoniche favorisce l'instaurarsi del fenomeno carsico per la più lenta percolazione delle acque meteoriche.

L'analisi petrografica di 38 campioni di vari litotipi calcarei raccolti a caso nella area campione ha smesso in evidenza che la comparsa di micro-forme da stress prevalentemente tettonico, è più frequente nei calcari granulo-sostenuti e in quelli cristallini piuttosto che in quelli fango-sostenuti. In conclusione, la ricerca dimostra ancora una volta l'esistenza di alcune correlazioni non solo qualitative, tra la frequenza delle varie forme carsiche superficiali e il grado di fratturazione delle rocce, la morfologia del rilievo, la tipologia petrografica.

TERMINI CHIAVE: Carsismo, Discontinuità delle Rocce, Sistemi di Informazione Geografica, Microtettonica, Abruzzi.

INTRODUCTION

Due to the weight of overlying materials, to confining rock pressure and to past tectonic activity, a non-zero-stress component is assumed to occur in each rock mass (Goodman, 1989). Several rock joint-sets commonly cross-

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TABLE 1 - Occurrence of two more frequent density classes in the Land Management Units

Code	Land management unit Geology	Geomorphology	Lithology	1° jointing density class (%)	2° jointing density class (%)
01	System of continental Quaternary age formations	terraced floodplains and fans	mostly calcareous gravel, sand and silt	DET (92.39)	MA2 (2.24)
02		alluvial plains and fluvial lacustrine surfaces	mostly calcareous gravel, sand and silt; travertine and pyroclastic material	DET (76.38)	MA3 (8.28)
03		mainly Holocene terraced alluvial plains	silicate and calcareous sand and silt	DET (85.78)	MA3 (11.98)
04		Pleistocene scree deposits and stream fans	mainly calcareous mixed textured clastic sediments	DET (73.67)	MA3 (18.67)
05		Holocene scree deposits and stream fans	mainly calcareous mixed textured clastic sediments	DET (66.19)	MA3 (11.64)
06		tectonic-karstic basins and dolines	silty clay sediments	DET (71.02)	MA2 (7.70)
07		fluvial-glacial surfaces and moraines	calcareous mixed textured clastic sediments	DET (83.02)	MA3 (10.68)
08		terraced fluvial-lacustrine high plains	calcareous breccia and silt	DET (89.06)	MA2 (4.72)
09	System of marine terrigenous formations (Mio-Pliocene in age)	hillslopes, mounds and valleys	calcareous gravel and conglomerate	MA3 (47.25)	MB3 (20.06)
10		hillslopes, mounds, divides and valleys	sandstone and claystone of «Laga Flysch»	MA4 (53.87)	MB4 (31.56)
11		hillslopes, mounds, divides and valleys	claystone, sandstone, marl of «Laga Flysch»	MB4 (41.14%)	MA4 (38.14%)
12		undulating hillslopes, mounds and valleys	marl and claystone	MB4 (54.11%)	A3 (12.83%)
13		convex hillslopes and small valleys	marly limestone, marl and calcarenite	MA3 (47.51%)	A2 (13.25%)
14	System of marine carbonate formations (Meso-Cenozoic in age)	mounds and summits with occurrence of karstic features	limestone and dolostone	MA3 (41.26%)	A3 (17.82%)
15		convex and long slopes	marly limestone, marl and calcarenite of «Scaglia Formations»	MA3 (49.16%)	A3 (20.91%)
16		rock cliffs, mounds, rock hillslopes and valley cutting	limestone, dolostone, calcarenite	MA3 (49.16%)	A3 (20.91%)

fractured with similar solid angles act to modify the rock masses continuity and volume (Hoek & Bray, 2001; Priest, 1993; Selby, 1993).

Some studies carried out previously on the Gran Sasso Range and nearby (Monti della Laga) in Province of L'Aquila (Abruzzo, Italy) (Lorè & Magaldi, 2000; Lorè & *alii*, 2002; Magaldi & Tallini, 2002) have noted the relationships among the rock fracturing degree (for example, jointing density expressed by number of fractures per km) from macroscopic field observation and aerial photos survey and the karst landforms.

This research deals with the identification of semi quantitative relation between some geo-structural and morphologic elements and karst features using geographic information system (GIS) and petrographic technique.

ROCK JOINTING DENSITY AND ORIENTATION OF THE FORMATIONS

A study area was selected some years ago inside the Gran Sasso Range. The area includes the main part of the Sasso Massif comprising carbonate formations Triassic to Miocene in age and very limited outcroppings of Miocene sandstones and marls (the Laga Mounts Flysch formation) (fig. 1). A provisional unpublished map of rock jointing (fracturing) was completed some years ago by a private Societies group (CISE-TELESPAZIO, Milan and Rome, respectively). This map was subsequently revised and digitised at the DISAT Engineering Geology Laboratory (fig. 2) and a comparison was made with the Map of Management Units (MU) of the Gran Sasso area produced by Magaldi & Tallini, (2002), (fig. 3) using the ILWIS GIS (ITC, 2001) software package. Detritus covering large zones of the study area was considered as the maximum jointing class (fractures = more than 50 /m).

Some important consideration were obtained by the analysis of figs. 2, 3 and tab. 1:

1) the detritus cover is always occurring in all MU but it is particularly spread on the Quaternary fluvial, fluvio-lacustrine, fluvio-glacial and scree materials (codes 01-08);
2) the Flysch formations and marly limestones (codes 09-13) are scarcely covered by poorly weathered coarse detritus probably being low both mechanical and chemical strength of the lithotypes;

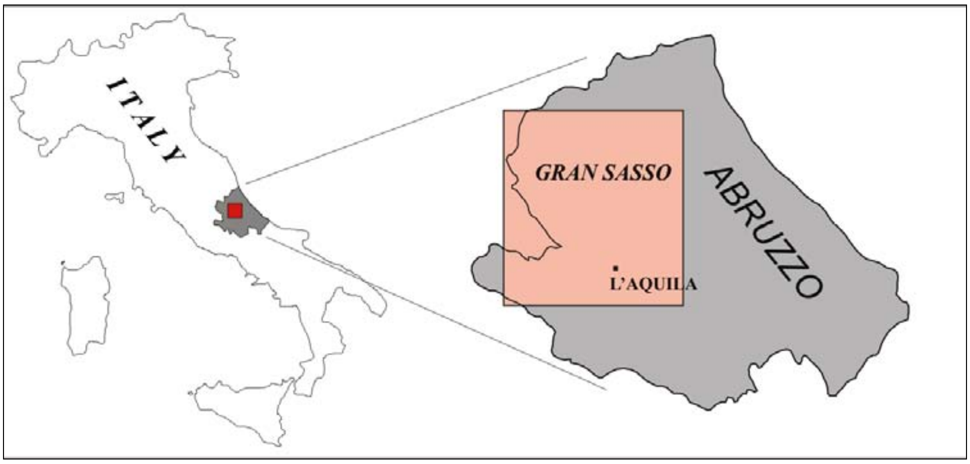


FIG. 1- Location of the sample area.

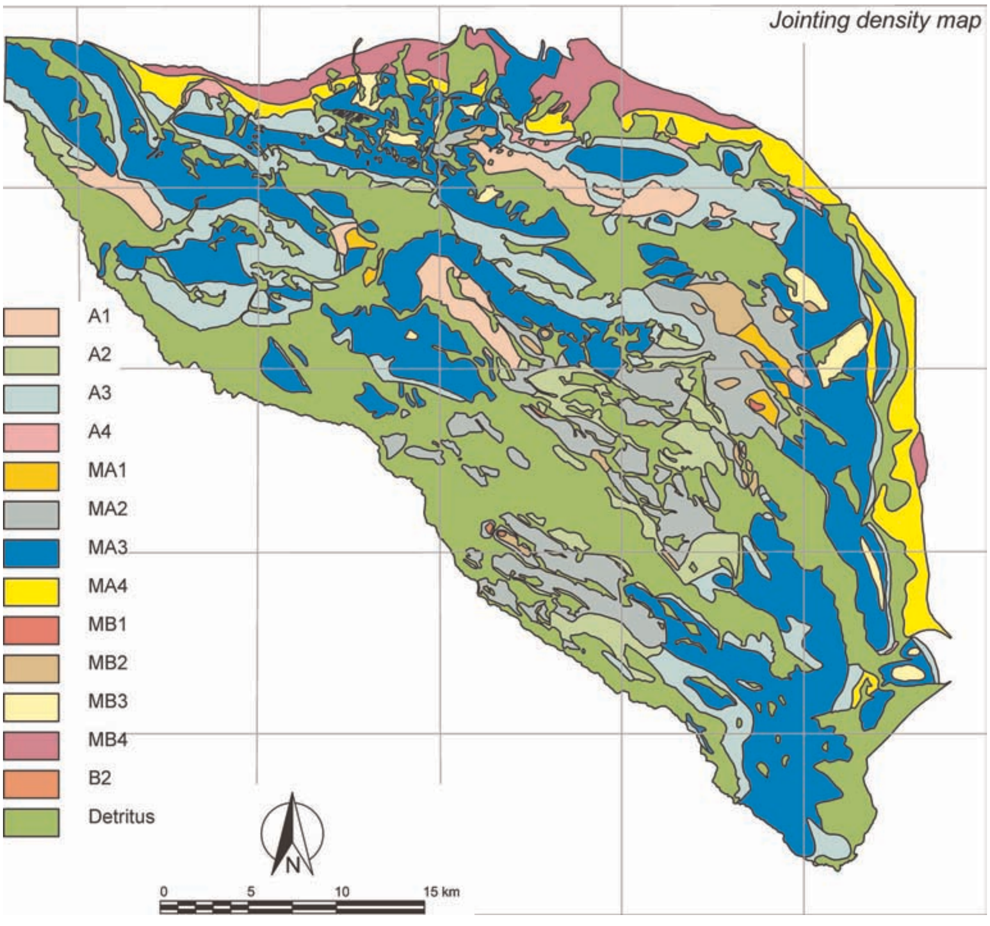


FIG. 2 - Jointing density map of the Gran Sasso Massif and nearby areas. Density classes are indicated by alphanumeric symbols. Literal symbols express the jointing degree class: A = high density (20 to 50 fractures/m); B = moderately high density (20 to 5 fractures /m); MB = moderately low density (5 to 2 fractures /m); B = low density (less than 2 fractures/m). Numerical values are relating to lithology of geological formations: 1 = massive limestone; 2 = marly limestone 3= well stratified calcarenites and marls; 4= Laga Mt. Flysch (mainly sandstone and clayey marl); DET = detritus cover which was assumed as the highest jointing class (more than 50 fractures/m).

3) most of carbonate formations (limestone, dolostone, marly limestone and calcarenites, codes 14-16) show moderately high to high jointing degree and frequency of the jointing density classes over the area is irregularly distributed (fig. 4).

In order to collect more information on geostructural aspects of the study area 51 structural stations were investigated for determination of both morphometry and spatial orientation of the carbonate bedrock discontinuities. Stations were selected far from faults traces so avoiding the

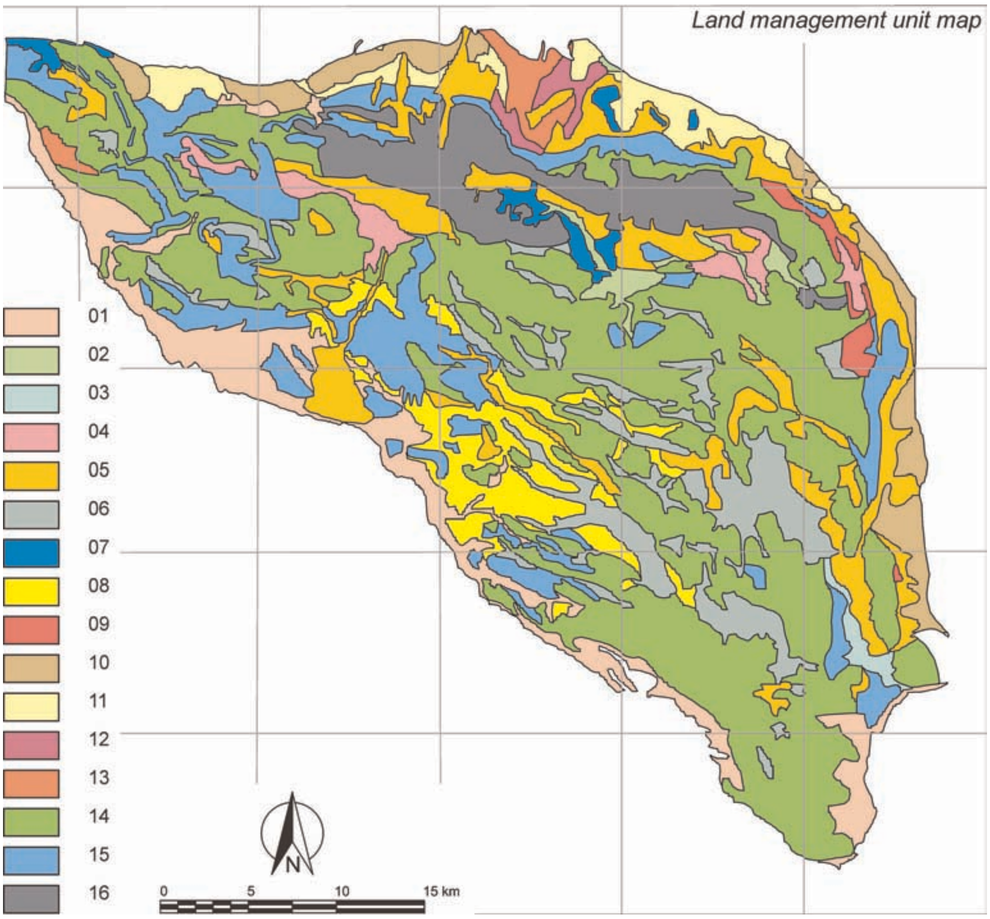


FIG. 3 - Land Management Units (LMU) Map (after Magaldi & Tallini, 2002). See legend in tab. 2.

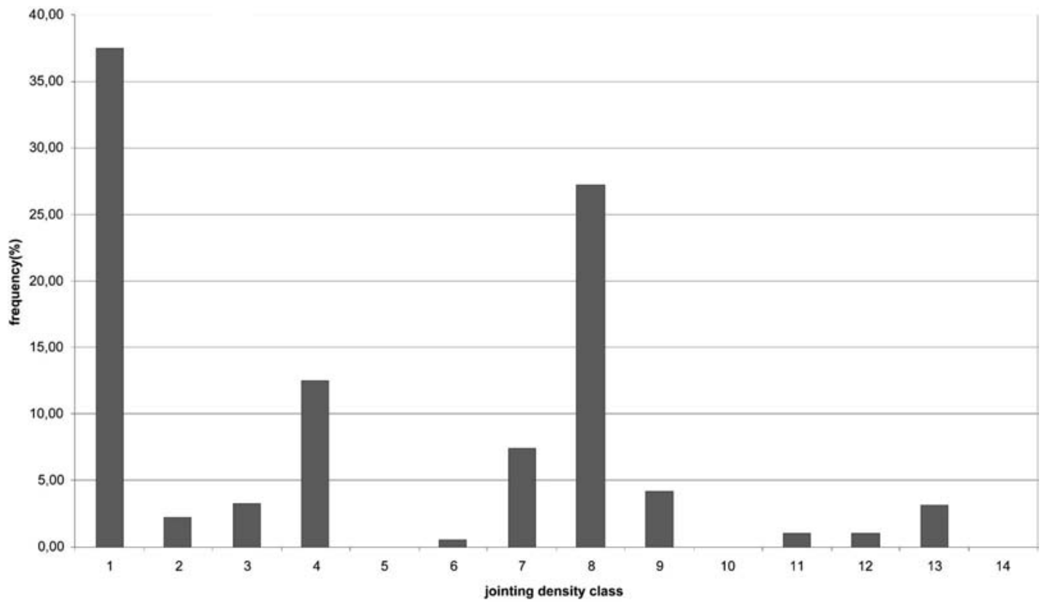


FIG. 4 - Jointing density class frequency over study area measured by pixels. Horizontal axis numbers refer to jointing density classes: 1 = Detritus; 2 = A1; 3 = A2; 4 = A3; 5 = A4; 6 = MA1; 7 = MA2; 8 = MA3; 9 = MA4; 10 = MB1; 11 = MB2; 12 = MB3; 13 = MB4; 14 = B. See legend of fig. 2.

dependence on local tectonic components. Results showed a random orientation of joint sets which possess nevertheless a very high dip (fig. 5). Moreover a relationship was observed between litho-static load over sampling station and the average joint opening (fig. 6) so suggesting that deeper joints could be larger than shallow ones.

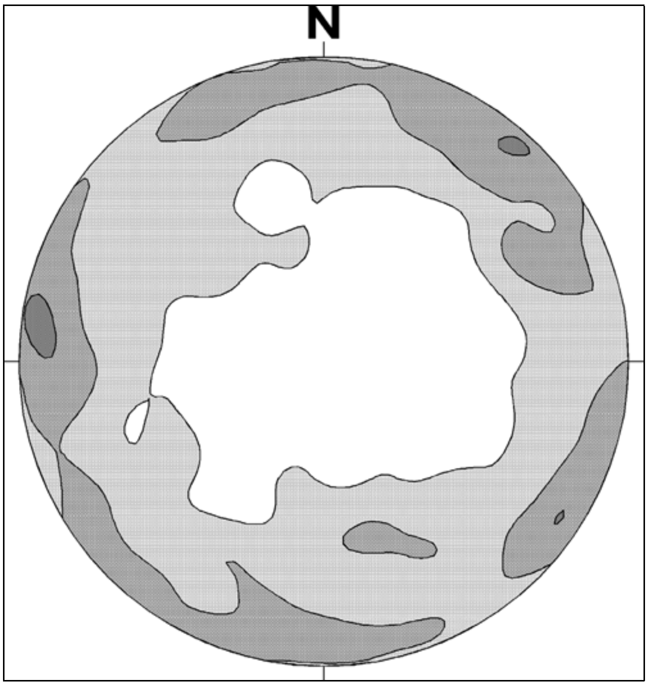


FIG. 5 - Contour plot of the joint poles (n = 1025) for 51 stations, lower reference hemisphere. Contour colours of equal pole densities relate to percentages as follows: pale grey = less than 10%; Intermediate grey = 10% to 20%; dark grey = more than 20%.

Small extension fractures (cracks) which are commonly filled by carbonate sparitic crystals sometimes occur across the rock. Their formation is commonly believed to be derived from a stresses field with vertical stress equal to weight of overlying rock acting together a tensional horizontal stress (Montone & *alii*, 1999).

STRESS FEATURES OBSERVED BY POLARISING MICROSCOPE

Rock masses are normally submitted to stress which is stronger depending on the whether the rocks originate from deep in the earth's crust and their geological age and tectonic history.

Due to the landscape modelling processes and also to some human activity (e.g. tunnel excavation) the stresses field is likely to change over time thus generating joints by shear and tension processes. These are likely to involve deformation of physical properties of mineral crystals at macroscopic and microscopic level. In order to highlight stress-induced morphologies on limestone minerals (calcite and dolomite), 38 samples from the main limestone rock types occurring (Mudstone, Wackestone, Grainstone etc, with 48 to 90% of calcium carbonate) were randomly collected for thin section observation. Lithotypes names are after the Dunham's Carbonate Rock Classification (1962).

Taking into account the information from micro tectonics research (Passchier & Trouw, 1998) some features assumed to be caused by geologic stresses, were identified for each sample. The features considered are believed to have been formed in natural stress fields with temperatures not higher than 200 °C. These are as the follows:

- massive veins: veins due to traction fractures filled by spatic calcite and dolomite crystals;

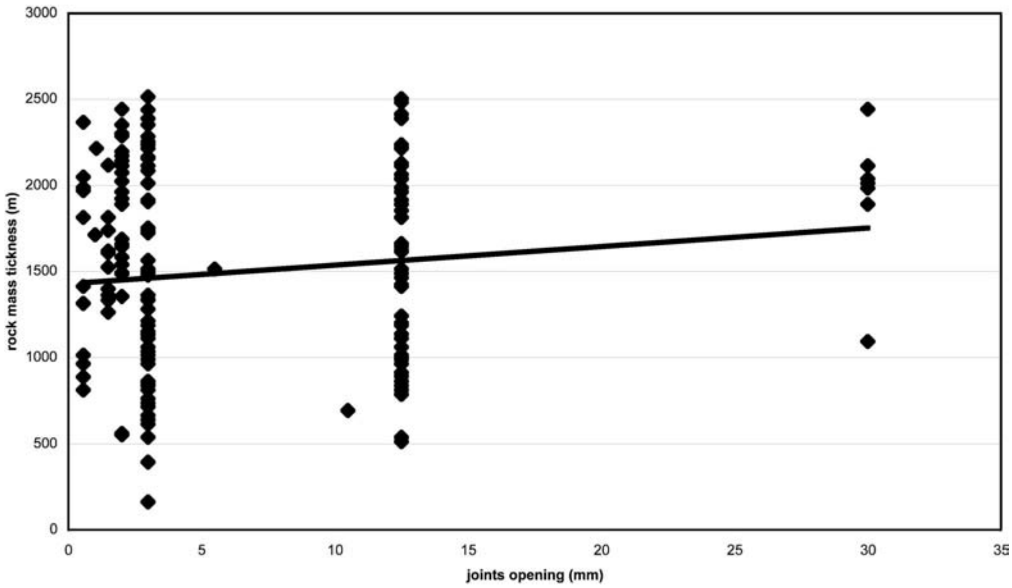


FIG. 6 - Relationship between litho-static load over sampling station (from rock mass thickness) and the average joint-opening.


Distribution scheme of karst landforms in the Gran Sasso massif
V shaped dry valley
Flat bottom dry valley
Pinnacle
Karrenfelder
Swallow hole
Isolated doline
Doline field
Uvala
Polje
0
5
10 km
Original data from field survey at 1:10000 scale

- fibrous veins: similar to previous ones, are supposed to derive from fractures filled by fibrous carbonates during the movements of both edges of cracks;
- calcite and dolomite crystals with undulatory extinction: secondary carbonate crystals occurring in rock voids which show undulatory extinction in crossed polarisers nicols;
- calcite twinning types: 3 types are assumed to be related to temperature of diagenetic-tectonic environment; type I is calcite twins crossing each to others with no right angles which formed at T < 200 °C; type II shows large twin bands in crystals and developed between 150-200 °C; type III, developed at T > 200 °C, appears to be twinned by bands crossing at right angles.

We interpreted the occurrence of the above features as due to the effect of general geologic stress at different temperature. Then a tentative quantification of phenomena was carried out by attributing a conventional rating to each observed feature (tab. 2). Thus, Principal Components Analysis was applied to the carbonate rock stress features taking into consideration the rating of each features. After some elaborations, a diagram with 4 representative point-clusters was produced (fig. 7). Horizontal axis is mainly depending on elevation of sampling location whereas the vertical one is assumed to be the expression of stress features relevance. A detailed check of the cluster contents shows some relationships with the carbonate rock stiffness: cluster 1 groups almost completely Wakestone samples; cluster 2, various lithotypes; cluster 3, almost completely Crystalline Carbonate; cluster 4, two grain-supported samples (Packstone and Grainstone) from highest elevation sites.

KARST LANDFORM IN RELATION TO ROCK JOINTING

The rock fracturing conditions of carbonate formations are likely to increase the karst processes by the forming of preferential way for penetrating waters (Ford & Williams, 1989; Klimchouk & *alii*, 1996).Then a comparison among jointing class and surface karst landform was carried out by normal GIS analysis. The karst landforms distribution is shown on the out-of-text Table. Due to scale some features were omitted.

TABLE 2 - Stress micro-features in carbonate rocks and assigned rating for their occurrence in rock thin sections

Features	Rating
massive veins	2 to 3 in relation to width
fibrous veins	2
calcite crystals with undulate extinction	2
calcite twinning type I	2
calcite twinning type II	3
calcite twinning type III	4

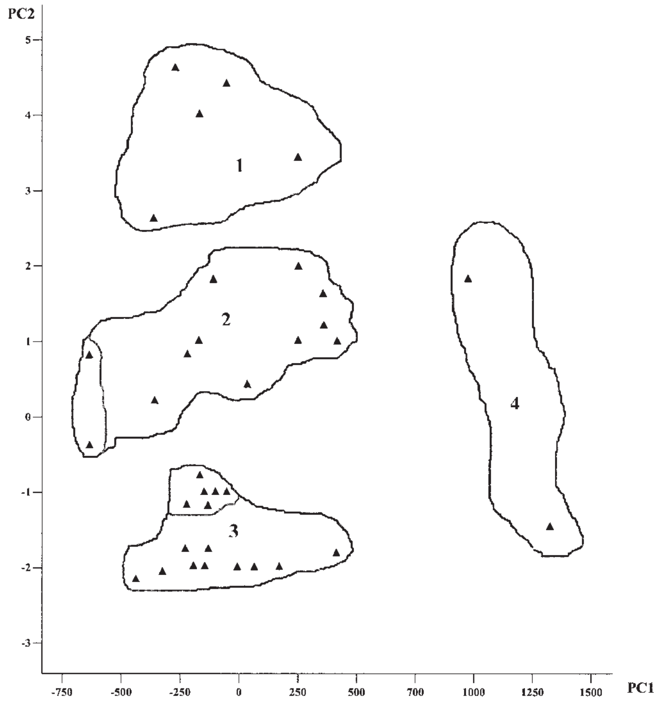


FIG. 7 - Clusters derived from Principal Components Analysis applied to stress micro features, X axis being related to elevation, Y axis to stress of sampling location. See text for more explication.

Some karst landforms are expressed by single point (pixel) as well by polygons; then a «karst density» occurrence was considered which represents the ratio between total area of karst feature and total area of related jointing class. Single pixel size for both areas was 30 m x 30 m.

Karst features which were recognised are the following (organized from single-pixel (point) forms to multi-pixels (polygonal) forms):
PI = pinnacle, IS = isolated doline, SW = swallow hole, KA = karrenfelder (point forms);
MO = monogenetic doline, UV = uvala, DO = doline field, PO = polja, (polygonal forms).

Due to their limited extension karren fields were associated to single pixel forms fig. 8 and fig. 9 show relationships between karst forms frequency (karst density) and jointing density for point and polygonal landforms respectively.

A correlation analysis (Spearman' rho test) between the jointing density and karst landforms frequency was carried out by aggregation of the forms in point and polygonal forms (tab. 3). So an inverse correlation could be assumed to occur between the jointing density and karst forms frequency which appears to be significative for both the polygonal and point forms.

It is so reasonably to conclude that a fast water infiltration into bedrock should inhibit or slacken the more large and complex features formation. Furthermore the minimum density value of jointing and maximum density of polje are strictly correlated.

TABLE 3 - Spearman' rho test between the jointing density and karst landforms frequency carried out by aggregation of the polygonal and point forms

Polygonal forms (n = 16), rho = – 0,637	(p < 0,001)
point forms (n = 14), rho = – 0,645	(p < 0,01)

Some other relationships were successively evaluated for the karst landforms. Firstly, the DEM (1:25,000) was used for slope-angle vs. karst features, deriving the coefficient of determination from the pixel number of the area of both slope and landform. The correlation between hill slope values and related karstic landforms density (area in pixels) was further assessed after Pearson' test. The test was applied individually considering all karst features. Except for pinnacles, a significant inverse correlation accounted for slope values and karst density so denoting the relief influence on the karstic process to form (tab. 4). This negative correlation could be explained considering that karst activity is more intense where the water-rock contact is longer over time: so the well known planation of some karst landscape could be assumed to be the result of cause and effect of past karstic process. No or very low significant correlations were observed for features of high relief such as pinnacles because their distribution depends on the joints occurrence.

Successively a relationship between main tectonic discontinuities (faults) and karst landforms was considered after some evidences coming from previous unpublished reports and other researches (Lorè & *alii*, 2002, Ford & Williams,1989; Hantke & Scheidegger, 1999). All mapped faults (Ghisetti & Vezzani, 1998) were digitised and

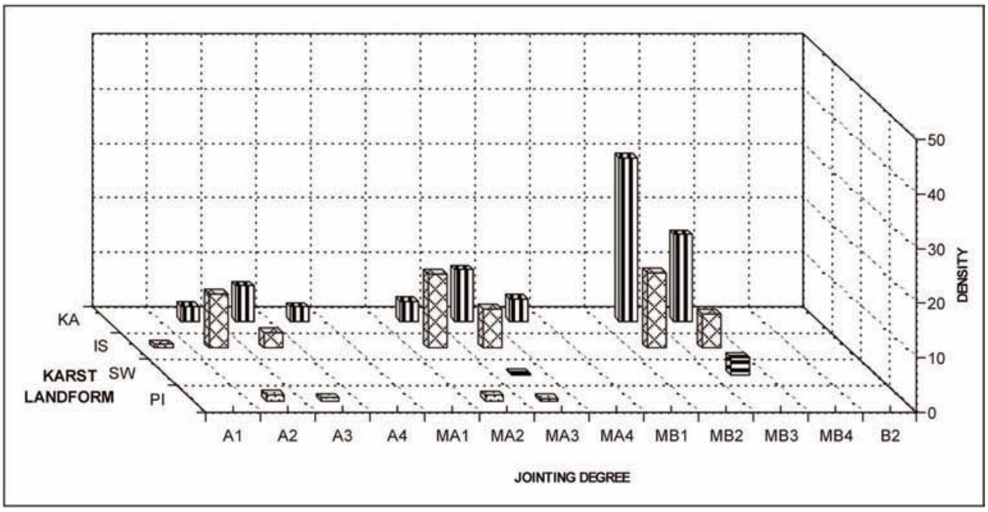


FIG. 8 - 3-D diagram of point karst landforms density in relation to the jointing density classes (density x 10^{-4}): PI = pinnacles; IS = isolated doline; SW = swallow hole; KA = karrenfelder. The jointing degree classes are arranged from highest to low class, detritus cover and Laga Flysch rocks being non considered.

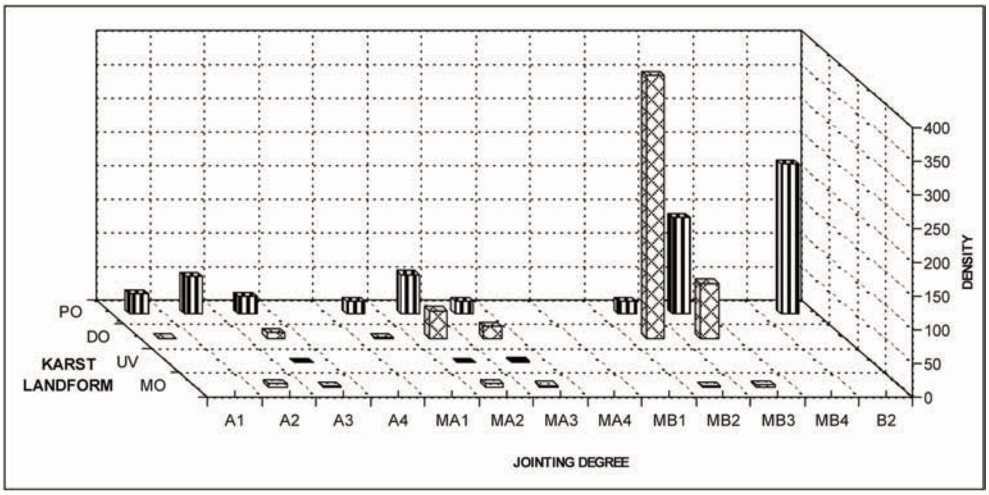


FIG. 9 - 3-D diagram of polygonal karst landform density in relation to the jointing density classes (density pixels x 10^{-3}): MO = monogenetic doline; UV = uvala; DO = doline field; PO = polja. The jointing degree classes are arranged from highest to low class, detritus cover and Laga Flysch rocks beingnon considered.

TABLE 4 - Pearson's coefficient of the correlation between slope-angle and karst landforms density

	Doline field	Monogenetic doline	Polja	Uvala	Isolated doline	Pinnacles	Swallow hole	Karrenfelder
N. pixel vs. slope angle	– 0.765 $p < 0.0001$	– 0.873 $p < 0.0001$	– 0.839 $p < 0.0001$	– 0.721 $p < 0.0001$	– 0.561 $p < 0.01$	– 0.139 n.s.	– 0.577 $p < 0.01$	– 0.436 $p < 0.001$

TABLE 5 - Pearson's coefficient of the correlation between karst landforms distribution and their distance (m) from fault traces

	Doline field	Monogenetic doline	Polja	Uvala	Isolated doline	Pinnacles	Swallow hole	Karrenfelder
N. pixel vs. distance from fault	– 0.625 $p < 0.0001$	– 0.750 $p < 0.0001$	– 0.742 $p < 0.0001$	– 0.621 $p < 0.0001$	– 0.568 $p < 0.0001$	– 0.421 $p < 0.01$	– 0.292 n.s.	– 0.460 $p < 0.0001$

elaborated for direction, linear extension and frequency over the land (fig. 10). By combining the geostructural map with the karst landform one, a table was obtained showing the Pearson's coefficient for karst landforms vs. their minimum distance from fault traces (tab. 5). As it was foreseeable the karst landforms appears to be inversely related to the distance from faults that are likely to be associated with main karst landform (e.g. polje). Starting from previous results on rock jointing, a further distribution was elaborated that shows the relationship (fig. 11) between fault distance (metre) and jointing density (j.d., expressed by fractures number/metre). These results lead to the conclusion that the occurrence and proximity of faults could increase the fissure-permeability value of the rocks.

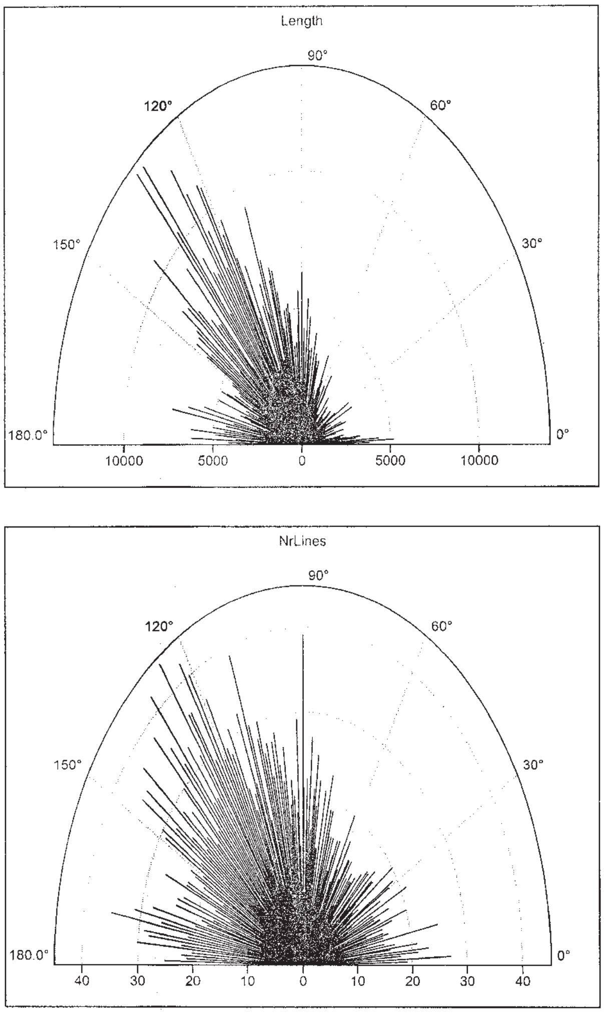
CONCLUDING REMARKS

This research has taken following items into account:

- the jointing characteristics of limestone formations on Gran Sasso Range;
- the stress micro-features recorded in limestone;
- the type and occurrence of polygonal and isolated karst landforms;
- the relation between the jointing density and karstic landform.

The joint sets of the Gran Sasso - Mt della Laga Park are sub vertically dipping being formed by a vertical lithostatic loading that was able to produce the fractures that increase with the thickness of rock mass. Subsequently the permeability could increase with the rock mass deepening. The orientation of the joints could also explain the high water infiltration power of the Massif. All results of this research point a very close correlation occurring between the karst landforms distribution and the geomorphologic and structural aspects of carbonate bedrock.

(a)



(b)

FIG. 10 - Rose diagram of the fault direction and length (a) and the fault direction and number (b).

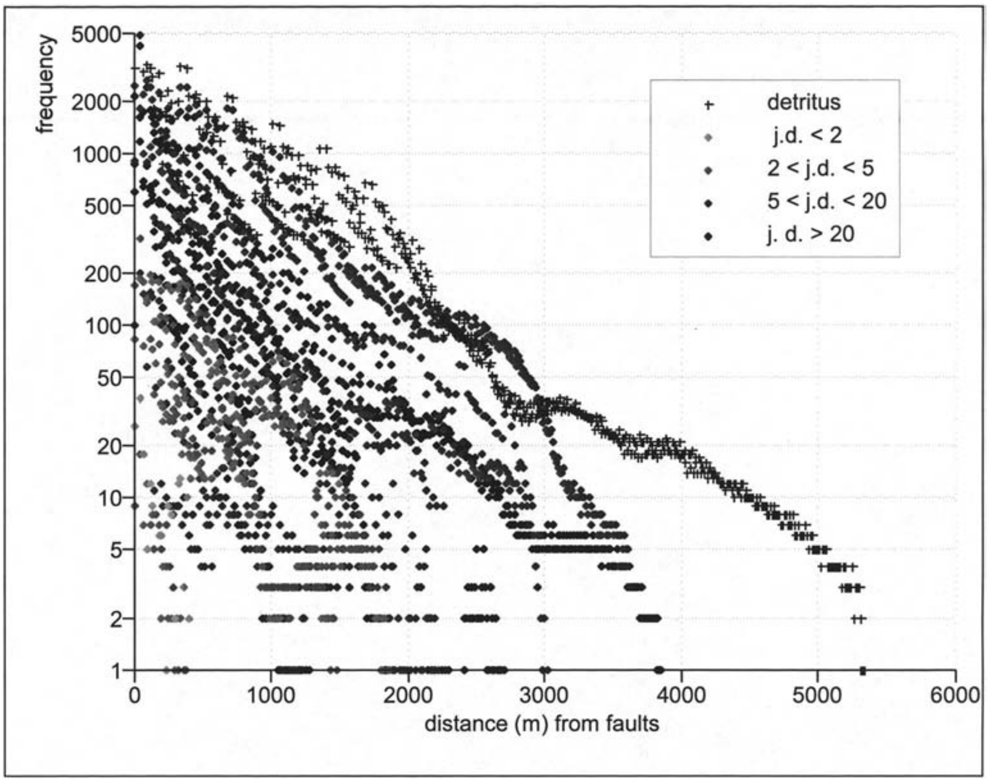


FIG. 11 - Frequency of pixels belonging to different jointing density classes (j.d. = fractures number / m) vs. distance (m) from faults.

Both isolated and polygonal-form distribution is favoured by scarcity of joint sets and fault traces. It is particularly evident that the longer the CO_2 rich water was in contact with the carbonate bedrock (probably trough a thick «terra-rossa» cover soil) the larger and more evolved was the type of landform that was produced. We conclude that the high degree of rock jointing is favouring a rapid water penetration thus hindering the complex karst landform genesis.

The stress micro-features are mainly occurring in the best-textured limestone types which are also stronger, less fractured and probably more suitable to allow polygonal karst features to form.

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