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INFLUENCE OF GEOSTRUCTURAL CONDITIONS ON THE SPELEOGENESIS OF THE TRIESTE KARST (ITALY)

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(6 figures)

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SUMMARY. The Trieste Karst is a relative old karst that has been evolving for almost 10 million years: the initial superficial morphologies (planation surfaces which have evolved in the shape of polje system and deep collapse dolines) are difficult to distinguish. The cavities maintain rare primary morphologies filled by deposits, breakdowns and concretions, which at the same time modify other deep morphologies due to changes in the baseline level and adaptations to tectonic movements.
The comparison between structural setting of rocks and development directions of caves confirms the strict influence of geological-structural features on speleogenesis: the drainage network should have been mainly conditioned by the highest slope of the stratification (sometimes modified by intersections following a similar direction between strata and fracture plains). Secondary influences regard the presence of "opened planes" and those related to intersection lines between opened plains due to tectonics or structural features.

KEYWORDS: speleogenesis, cave development, Classical Karst.

RIASSUNTO.
Per una sistematica analisi dello sviluppo delle cavità del Carso triestino è necessario comprendere i condizionamenti geologici (litologici e/o strutturali) che le hanno generate.
Sono stati elaborati i dati di 742 grotte, per un totale di 40,288 metri di sviluppi orientati, dei quali 24,061 metri rappresentanti 132 cavità a prevalente sviluppo orizzontale e 16,227 metri rappresentanti 610 pozzi.
Inoltre è stato considerato l'assetto spaziale dei piani di discontinuità in 96 stazioni di misura e dalle foto aeree sono state ricavate le principali lineazioni osservabili (Figs. 2 & 3).
Il Carso triestino è in evoluzione da più di 10 milioni di anni. Le originali morfologie superficiali sono di difficile riconoscimento: l'antica superficie d'abrasione si è evoluta in una serie di polje ad orientazione dinarica che conseguentemente all'abbassamento della superficie di base si sono evoluti in un plateau su cui si sono impostate numerose doline di dissoluzione e di crollo.
Le rare morfologie primarie presenti nelle cavità sono mascherate da successivi momenti di concrezionamento, sedimentazione e crollo. Inoltre si rilevano morfologie derivanti dalla variazione del livello di base e dagli eventi tettonici.
Il confronto fra la distribuzione areale dei litotipi (calcari, calcari dolomitici e dolomie), l'assetto strutturale (direzione ed immersione della stratificazione, dei piani di faglia, delle principali famiglie di discontinuità e dei lineamenti tratti da analisi fotogrammetrica) e le direzioni di sviluppo delle cavità, conferma lo stretto condizionamento imposto dalle caratteristiche geologico strutturali sulla speleogenesi e porta ad ipotizzare per i pozzi una genesi ed un'evoluzione lungo i piani subverticali più aperti tra quelli presenti nella compagine rocciosa ed in particolare lungo i piani di fratturazione N-S. Dato che i pozzi tagliano o complicano le cavità sub orizzontali o poco inclinate, è da supporre che si tratti di morfotipi generatisi dopo che nel massiccio roccioso si era instaurato il reticolo di drenaggio e deflusso generale (orientato in direzione NE-SW).
Dall'analisi sono state individuate cinque zone aventi caratteristiche geologiche, geomorfologiche e carsogenetiche differenti.
Nella zona delle "sorgenti di Duino" più del 40 % delle cavità si sviluppano verso NW e SSW (Figs. 2 & 4a); nel "plateau di Aurisina" si sviluppano preferenzialmente verso S e SW; nel "plateau di Monrupino le direzioni di sviluppo

sono maggiormente disperse con una prevalenza verso SW e W; nel "plateau di Basovizza" verso SE e NW mentre nell'area della "Val Rosandra" , che presenta un quadro geologico completamente differente (complicato da una serie di faglie inverse ad orientazione E-W) le cavità si sviluppano preferenzialmente verso N (12%), NE (13%), E (8%).
Questi risultati evidenziano come lo sviluppo preferenziale delle cavità avvenga lungo la massima pendenza della stratificazione (talvolta modificata da intersezioni a direzione simile fra piani di strato e piani di frattura).Condizionamenti secondari, talvolta prevalenti, sono da considerare quelli relativi alla presenza di "piani aperti" o di linee di intersezione di piani aperti per cause tettoniche o strutturali.
Le morfologie carsiche superficiali, così come oggi si possono osservare sono il risultato predominante dei condizionamenti litologici ed in parte minore di quelli tettonico-strutturali, infatti la massima pendenza della stratificazione e le intersezioni dei "piani aperti" per cause tettoniche, non hanno risultanze sulle morfologie superficiali come invece asserito nella bibliografia pregressa.

PAROLE CHIAVE : speleogenesi, sviluppo delle grotte, Carso.

RÉSUMÉ. L'analyse systématique du Karst de Trieste permet d'en comprendre les contingences lithologiques et/ou structurales et la genèse, sur base des données issues de 742 cavités, ayant 40.288 mètres de développement total, dont 24.061 m pour les 132 grottes subhorizontales étudiées, 16.227 m pour les 610 puits plus profonds que 50 m pris en considération. En outre, on a réalisé une campagne d'étude sur le terrain avec 96 stations pour mesurer les accidents géologiques et tectoniques et une étude des photos aériennes pour cerner les éléments géologiques (Figures. 2 & 3).
Le Karst de Trieste est un ancien karst qui évolue depuis 10 millions d'années au moins. Les formes superficielles originelles sont très difficiles à reconnaître: l'ancienne surface d'abrasion a évolué en plusieurs poljes allongés selon la tectonique dinarique. De nombreuses dolines d'effondrement et de dissolution s'y sont ouvertes lorsque le niveau de base a baissé. Les cavités montrent rarement les morphologies primaires car elles sont remplies de plusieurs générations de concrétions, de sédiments et d'éboulis; en outre elles renferment de nombreuses morphologies dérivées à cause des changements du niveau de base et de la tectonique.
On a comparé la distribution des lithotypes et le classement géostructural (direction et pendage des plans de stratification, des plans de faille et des familles de fractures, direction des linéaments par photogrammétrie) avec les directions de développement des cavités. Presque 30% des puits sont organisé sur des fractures N-S, direction des efforts géologiques actifs. Comme les puits recoupent ou compliquent les galeries qui constituent la première structuration endokarstique, on doit supposer qu'une seconde phase de karstification verticale a été provoquée par l'accroissement du gradient hydraulique guidé par une phase tectonique de compression N-S.
On peut reconnaître cinq zones ayant un statut géomorphologique, géologique et karstogénétique différent dans un cadre suffisamment unitaire et justifié par le rangement structural.
Dans la "zone des sources de Duino" plus de 40% des cavités ont des directions de développement entre le NW et le SSW (Figures. 2 & 4a). Dans la zone du " plateau Aurisina ", elles se développent pour la plupart entre le S et le SW. Dans le "plateau de Monrupino", les directions de développement sont variables mais en majorité entre le SW et l'W. Dans la zone du " plateau Basovizza ", elles se situent entre le SE et le NW. Enfin, dans celle de "la vallée du Rosandra", le cadre géologique est tout-à-fait différent (des plis sont compliqués par des failles inverses E-W) et les cavités se développent de préférence vers le N (12%), le NE (13%) et l'E (8%).
On peut voir que la spéléogénèse est strictement liée à la géologie: le développement préférentiel est dans la direction du maximum pendage de la stratification quelque fois modifié par l'intersection avec des plans de fractures caractérisés par une direction presque parallèle.
On constate en plus l'influence des fractures ouvertes et de leurs points. La structuration endokarstique a eu comme contingence prédominante la lithologie et la structure, plus précisément le pendage maximum de la stratification et les directions d'intersection des plans tectoniques ouverts, et non pas la morphologie extérieure comme l'ont affirmé les anciens Auteurs.

MOTS-CLES: spéléogénèse, développement des grottes, karst classique.

1. Introduction

All the caves within the carbonatic sequence of the Trieste Karst have been thoroughly analysed, since both the genesis and development of the hypogean karst are greatly affected by the spatial distribution of rock discontinuities in the initial phase of the speleogenesis. The geomorphologic structural analysis of the geometrical characteristics of caves has been completed by the study of the geological setting of carbonatic platform.
Data of 742 caves have been processed : the result is 40,288 km of well defined structures, among which 24,061 km represent 132 caves with a prevailing horizontal structure and 16,227 km correspond to 610 holes.

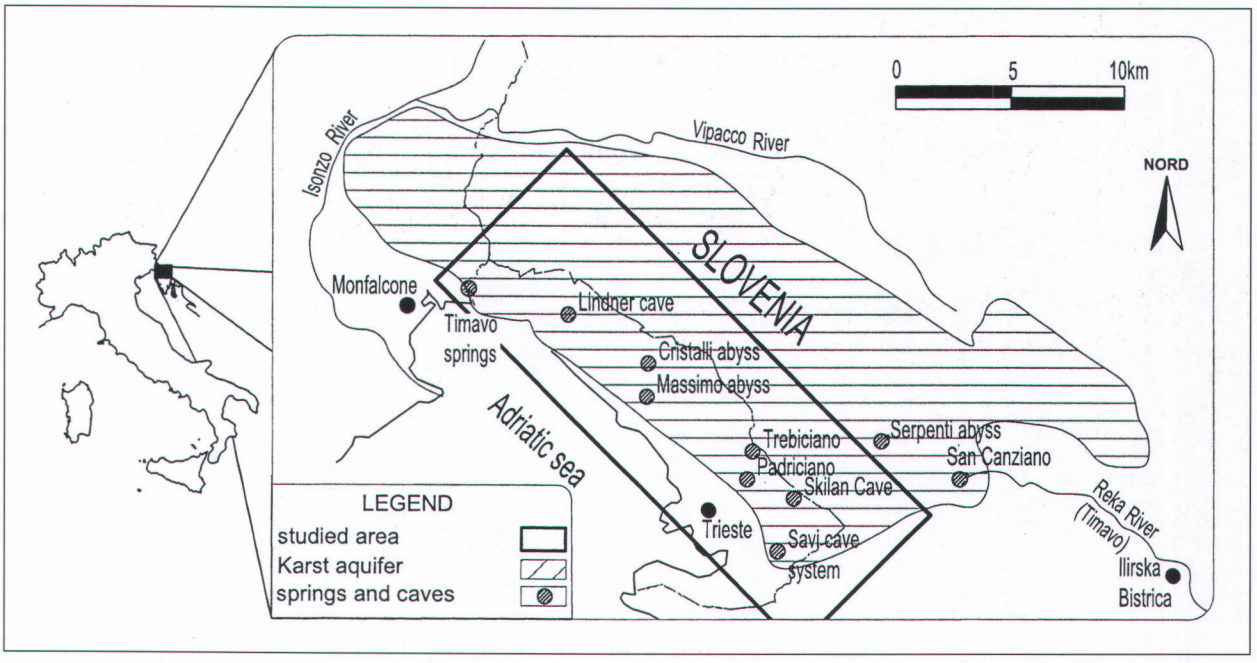


Figure 1. Trieste Karst and its main caves.

A field survey of geological-structural features has also been performed: the spatial distribution of the discontinuities has been measured in 96 measuring stations of the tridimensional setting, regularly disposed along the territory (Fig. 1).

The plateau, with an extension of about 60 km^2, can be considered as a mature karst; a great variety of hypogean and superficial morphologies have originated and developed under the influence of lithology and tectonics since the Pliocene to the present. The area is not subject to seismic activity, but it is important to remind of the large quantity of earthquakes, both in the past and at present, in Friuli and Slovenia.

Processed data have been compared to graphs indicating the different development directions, allowing some hypotheses on the influence of geological conditions on the speleogenesis and development of the caves.

2. Lithology and tectonics

From the geological point of view, the Trieste Karst represents the southern sector of a slightly asymmetrical anticline with general NW-SE direction. The bedding presents an average dip of 10°-30° southwards, abruptly increasing along the edge of the karst plateau. It becomes subvertical or reversed close to the coast. Evidence of the very complex, prevalently compressive tectonics due to Dinaric and Alpine phases in a regional structural frame are present only in restricted areas.

The outcropping sequence (Cucchi *et al.* 1987) is divided in several Cretaceous-Eocene lithological units. From bottom to top we find:

- dark-grey limestones frequently bituminous, with evident centimetric-polydecimetric bedding, and interbedding limestone-dolomite, thickness 300-370 m (*"Mt. Coste" Member* - Aptian-Albian - with a medium karstification);
- crystalline grey dolomites with frequent paleokarst pockets, decimetric, sometimes metric, bedding, thickness 300-600 m (*"Rupingrande" Member* - Albian-Cenomanian - with very feeble karstification);
- grey limestones with abundant rudist fragments, very frequent large fossiliferous, with massive bedding, sometimes not evident or with decimetric/metric period, thickness 350-1200 m (*"Zolla"* and *"Borgo Grotta Gigante" Members* - Cenomanian-Turonian in age - with very high and wide karstification);
- dark grey limestones sometimes bituminous, scattered breccia levels and fossiliferous limestones, evident bedding with decimetric period, thickness 120-480 m (*"Mt. Grisa" Member* - Paleocene - with a medium-low karstification);
- light or dark limestones, very fossiliferous, not very evident bedding with polydecimetric period, thickness up to 300 m (*"Opicina" Member* - Paleocene-Eocene - with medium-high karstification);
- marls and sandstones with very evident interbedding, thickness up to 500 m (silico-clastic turbiditic *Flysch Fm.* - Eocene - non karstifiable).

The geometry and the spatial order of joints have been determined in 96 stations, measuring in field the attitude of 100 discontinuity plans. Their graphical representation throughout poles on the Schmidt net has permitted to define the main groups (Fig. 2).

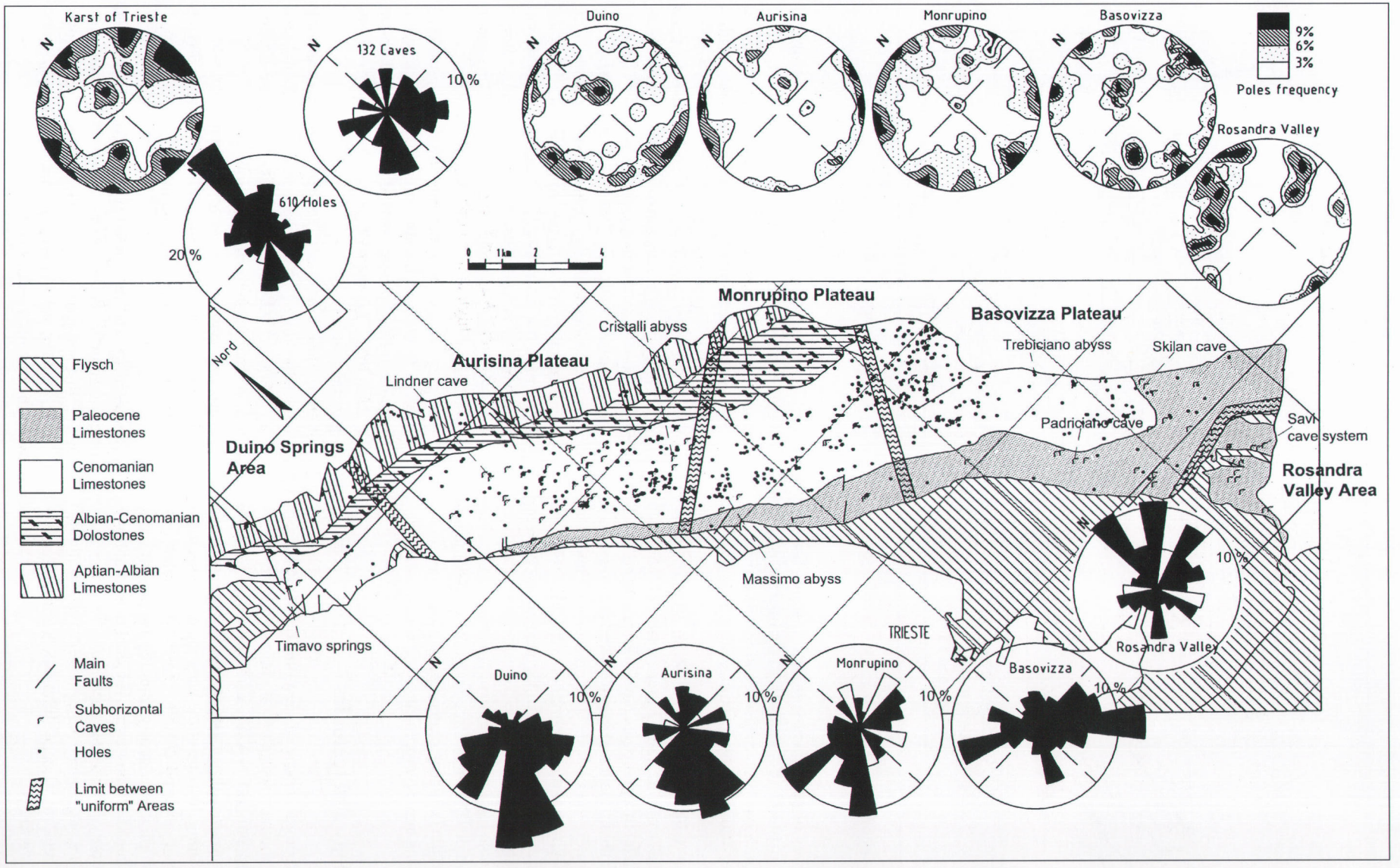


Figure 2. Geological map of Trieste Karst, with the feature of discontinuity plans in the whole area and in the several areas with uniform geo-structural geometry (poles of planes on Schmidt net, inferior hemisphere). The preferential directions of development of the 132 caves and the 610 holes analysed are here reported, as well as the five uniform areas described in the text: Duino springs area, Aurisina plateau, Monrupino plateau, Basovizza plateau and Rosandra Valley area.

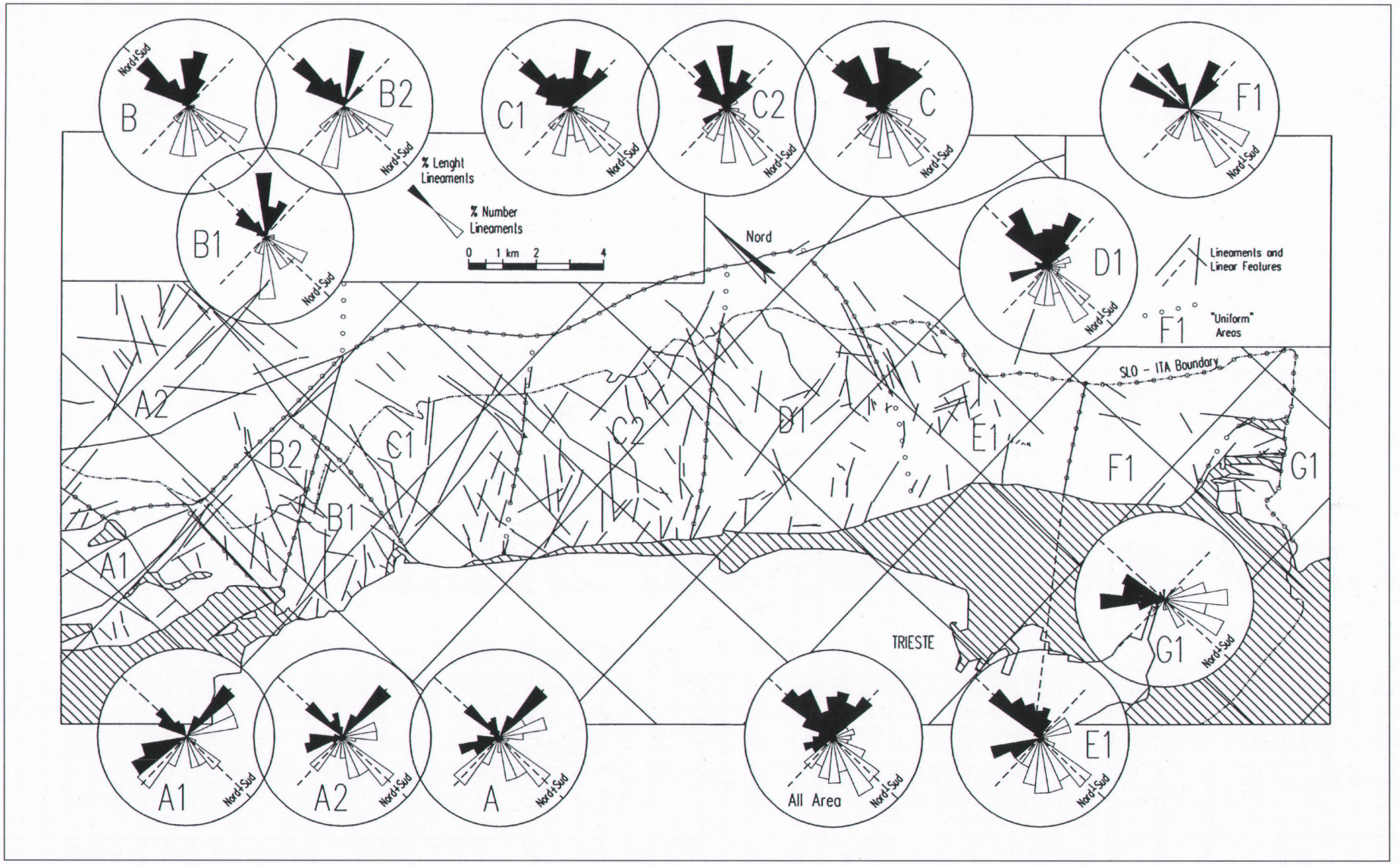


Figure 3. Distribution, length and direction of the spotted lines using aerophotogrammetrical analyses permit to subdivide the Trieste Karst in five main zones. B1 and B2: Duino springs area; C1 and C2: Aurisina plateau; D1: Monrupino plateau; E1 and F1: Basovizza plateau; G1: Rosandra Valley area. The percentage of the length of lineaments and linear features is given in black; the percentage of their number in white.

Using also aerophotogrammetrical analyses we have observed that the distribution, length and direction of spotted lines and the distribution of discontinuity planes permit to divide the Trieste karst plateau into five main areas with uniform structural geometry (Fig. 3).

3. Geomorphology

In the Classical karst area very karstifiable Cretaceous and Tertiary limestones crop out: they present all possible epigean and hypogean karst morphologies, with such density, width and typology as to make the area known as the symbol of karst morphologies. The Timavo River is a very well known example: it sinks into the San Canziano Caves (*Skocjanske Jame* in Slovenia) and, after more than 40 km of basically unknown hypogean flow, re-appears in San Giovanni di Duino characterised by impressive springs (Fig. 1). Apart from some small holes in the spring area, there are only three cavities (Serpenti Abyss - *Kacna Jama* in Slovenia, Trebiciano Abyss and Lazzaro Jerko Cave in Italy) sufficiently deep to affect with certainty the waters of the river branches; very few zones are affected by groundwater only during the maximum floods (Lindner, Skilan and Cristalli caves, Massimo Abyss).

The Trieste Karst reflects a relative old karst still evolving since almost ten million years (D'Ambrosi, 1971). The initial epigean morphologies, as the planation surface, which have evolved in the shape of polje system, and the deep collapse dolines are difficult to distinguish (Habic, 1984). The cavities maintain rare primary morphologies, today affected by filling deposits, breakdowns, concretions, which at the same time modify other deep morphologies due to changes in the baseline level and adaptations to tectonic movements (Cucchi *et al.*, 1983).

As to this point, there are two interesting cavities, the Skilan Cave (in the area surrounding Basovizza, still under exploration), with at least 6 km total length and 380 m deep (it reaches almost the sea level) and Savi - Fessura del Vento cave system, formed by 4+2 km of galleries and chambers located at the right side of the Rosandra creek.

In the studied area there are about 2000 cavities, among which only one thousand has size and development significant for statistical analysis. More than 700 of them have been surveyed well enough to permit a reliable analysis of the geomorphologic features.

On the basis of speleological surveys (plans and sections) for a total of 24,061 km, we have measured the length, dip and direction of some thousands of significant traits of 132 cavities. Moreover, we could define the attitude of about one thousand subvertical plans (joints or faults), which form 610 wells, for a total of 16,227 km in depth. The directions have been statistically analysed and we can say that more than 20% of the wells are structured following the North-South axis, whereas the caves with a prevailing horizontal trend are distributed quite regularly following the NNE-SSW, NE-SW, NW-SE, WNW-ESE directions.

A field survey has also been carried out to remark geological structural characteristics of the main underground systems found out in the Trieste karst carbonatic platform. The survey intended to discover concrete proofs of the agents that have mostly affected speleogenesis and evolution of the caves. As to the karst development, it has been proved that the Trieste karst plateau can be divided in five different areas with similar geological, geomorphological and speleogenetic features.

Each of them has uniform morphological (i.e. acclivity, distribution and size of the dolines), lithologic (substratum formed by more or less karstifiable limestones) and structural features (dip of stratification, spatial arrangement of discontinuities), which are rather different within every single zone.

4. Morpho-Geostructural units

We distinguished the "Duino springs area", the "Aurisina plateau", the "Monrupino plateau", the "Basovizza plateau" and the "Rosandra valley area" (Figs. 2 & 3).

More than 40% of the caves in the "Duino springs area" has a trend located in the WS sector, with cave traits that follow a basically W and SSW direction. As to this point, the trend of the flooded galleries feeding the three spring mouths of the Timavo underground river is quite significant. The almost 1 km of total length, formed by evident ramifications explored by divers up to 80 m below the sea-level, contains the joints N-S and NE-SW oriented as characteristic elements. 30% of the explored sectors shows SSW direction, whereas 20% of them is oriented westwards (Figs. 2 & 4A).

In the "Aurisina plateau" the caves course follows basically Sud and SW directions. In this sector it seems that the dip of the stratification and the groups of NE-SW faults were the elements that mostly influenced cave development. The Lindner cave is an example (Figs. 2 & 4B), since its trend is evidently linked to the SSW direction (25% of the cavity traits) and to the W direction (10% of the traits).

In the "Monrupino plateau" the directions of development are irregular, although it can be observed that they follow mainly E, SW, W directions. It is a very karstified area, where there are many cavities, noticeably developed according to the different preferential groups of discontinuity. The stratification ranges from sub-horizontal to low inclination and changes locally in direction. Due to this fact, the maximum slope of the stratification in this sector does not play an important role as far as spelogenesis is concerned.

In the "Basovizza plateau" the trend peaks are oriented SE and NW. Skilan cave is, owing to its extension and

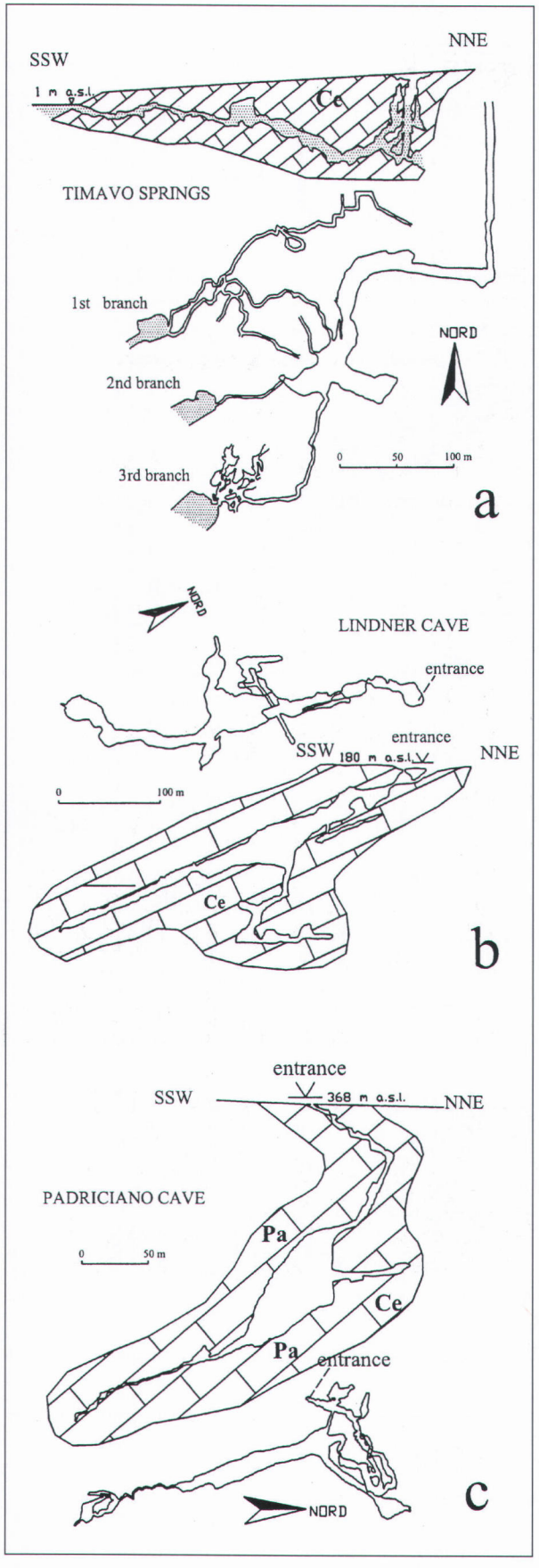


Figure 4. Maps and geological sections of the Timavo springs cave system (a), the Lindner cave (b) and the Padriciano cave (c).

complexity, the most representative and meaningful example of the whole studied area (Fig. 5). The cave, still under exploration, is among the deepest caves of the Trieste Karst and is up-to-now the broadest hypogean morphology, with a total length of over 6 km. The cave has developed in Tertiary-Cretaceous limestones and shows a prevailing extension following SE-NW direction, parallel to a fault and to strata direction. The most recent explorations have revealed also the presence of large, N-S structured shafts. The cave is formed by two main systems of galleries: the first, the smaller one, lies about 40 m below ground surface; the second is very large, with galleries reaching 60-70 m in diameter, located at about 200 m above sea-level. The hypogean system, and mostly the deep galleries, are filled by deposits (polygenic conglomerates, clay and sand) and by important collapses and breakdowns which have modified the primary morphologies almost completely.

Another characteristic cavity in this area is the Padriciano Cave, up to 1000 m long, with 20% of the total development oriented SSW, 15% WNW and 15% SE (Fig. 4C).

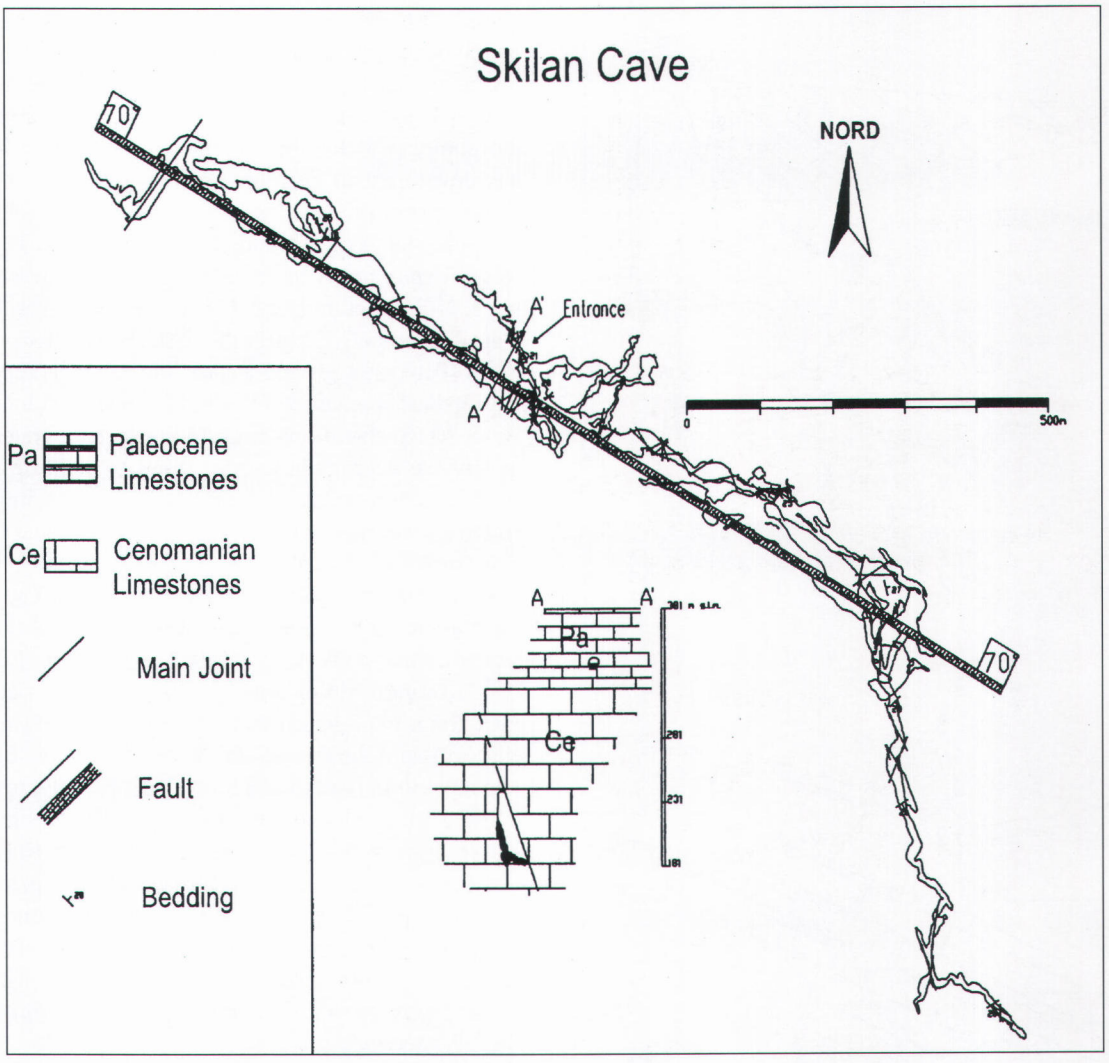
The "Rosandra valley area" presents a peculiar geological setting, in comparison with other zones of the Karst platform, and differences in the trends of development. The most important trends are N, NE, E, well correlated to the geological - structural features. The general tectonic feature of this area is the turning of the "Karst anticline", which transforms the Rosandra valley in a sort of restricted hinge zone. For this reason the structural model is very complex and the major discontinuities are due to the same overthrusts that have NW-SE direction and NE vergency are moved by many transversal (from N-S to NE-SW) secondary faults.

The system Savi - Fessura del Vento caves is located in the Rosandra Valley Tertiary limestones, in an area where intense tectonic influences have caused a series of overthrusts mixed with faults (Fig. 6). In the Rosandra Valley area, and in its caves, there are evidence of recent tectonic movements which have conditioned epigean (slope irregularities, falls and variations of directions along the course of the Rosandra creek) and hypogean morphologies (displaced solution forms, breakdowns and other morphologies).

5. Conclusions

The comparison between structural setting of the rocky volume and directions of development of the caves confirms the strict influence of geological-structural features on speleogenesis, and suggests that holes might have originated and evolved along very well marked subvertical planes among the limestones ones, especially along the N-S axis.

This leads to the supposition that, at the moment of karstification in vadose conditions (low aquifer and large aeration zone), N-S thrusts (faults and joints) prevailed,



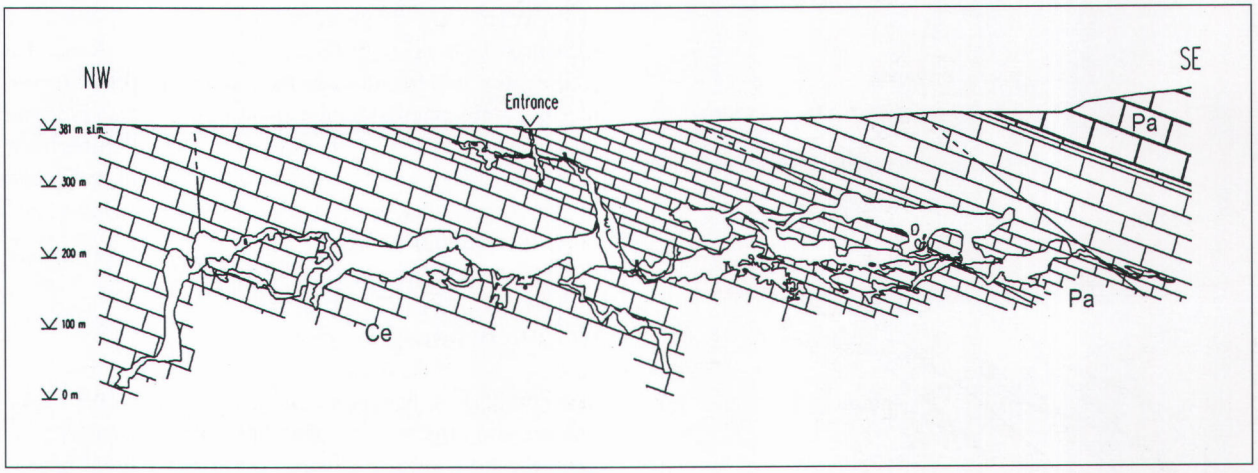


Figure 5. Plan with main discontinuity planes and geological section of the Skilan Cave.

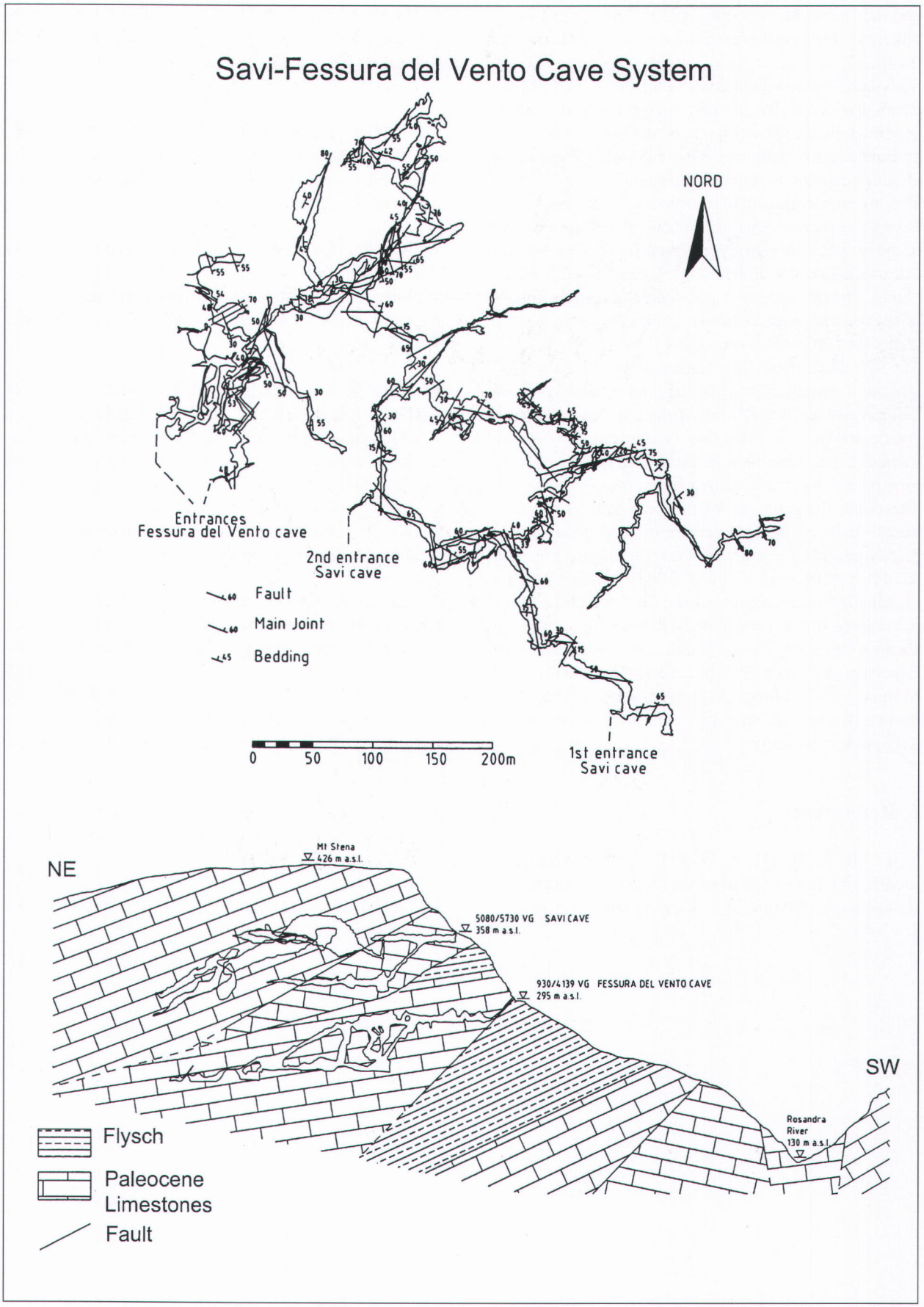


Figure 6. Plan with main discontinuity planes and geological section of the Savi Cave and the Fessura del Vento Cave.

and they were the only ones able to "open" fractures as pinch out, allowing the distribution of water and air within the rock.
Since holes cut or complicate subhorizontal or little sloped caves, they could be morphotypes originated after the general drainage system appeared within the rock, which probably occurred mainly following a NE-SW direction, although moving to another destination.
The above mentioned initial drainage network should have been prevalently conditioned by the highest slope of the stratification, sometimes modified by intersections following a similar direction between strata and fracture planes. The presence of "opened planes" and the lines of intersection of opened planes must be considered as other, sometimes prevailing, influences.
The first results from the comparison between lithology, structural arrangement, superficial morphology, and development and morphology of the cavities, lead to the conclusion that the main factors affecting the development of karst phenomena in the Trieste Karst are the geometry and the spatial distribution of discontinuities.
Therefore, the geometry of the cave network is conditioned firstly by the enlargement of voids along "open" discontinuities, secondly by the more or less limestone solubility (Cucchi et al., 1987, 1995) and the spatial arrangement of the various crossed lithotypes. The role of the superficial net, present in the outermost morphology, seems to be negligible, although it was considered very important in the past by some authors (D'Ambrosi, 1971; Marussi, 1975; Maucci, 1960; Mosetti, 1989). These morphologies are due to selective corrosion and geodynamic evolution.

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