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EFFECTS OF THE STRUCTURAL SETTING ON ENDOKARST SYSTEM GEOMETRY IN THE VALLE DEL NOSÊ (COMO LAKE, NORTHERN ITALY)

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(14 figures)

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ABSTRACT. The development and geometry of deep endokarst systems in the Valle del Nosê (Como Lake district, Northern Italy) is related to s setting in a synclinal structure. Endokarst development is controlled by bedding and jointing: most galleries and karst voids formed at the intersection of bedding planes with one of the two main discontinuity sets. Measurements inside caves and at the surface allowed comparing distribution and geometry of caves with the geometry of the main fold structure. The geometrical characteristics and the 3-dimensional arrangement of the studied endokarst system provide a powerful tool to determine possible underground drainage directions.

KEYWORDS: Cave systems, jointing, folding, Northern Italy

RIASSUNTO. Si riassumono brevemente i risultati di uno studio che ha avuto per argomento le relazioni tra assetto strutturale e carsificazione profonda della Valle del Nosê (Lago di Como, Italia Settentrionale), in una situazione strutturale di sinclinale. Si mostra che l'andamento dei sistemi carsici dell'area è fortemente condizionato dalla stratificazione e dalla fratturazione: in particolare, la maggior parte delle gallerie e dei vuoti carsici si è formata all'intersezione dei piani di strato con uno dei due sistemi di discontinuità prevalenti. L'analisi strutturale in grotta ed in superficie ha inoltre permesso di stabilire una relazione tra la distribuzione e l'organizzazione spaziale dei sistemi di cavità carsiche e la geometria della principale struttura plicativa: in questo modo è possibile spiegare in modo semplice ed efficace le caratteristiche geometriche dei sistemi osservati, fornendo un utile strumento previsionale per la determinazione delle possibili direzioni di drenaggio sotterraneo.

PAROLE CHIAVE: Grotte, fratturazione, piega, Italia Settentrionale

1. Geographical setting

The considered area is located in the so-called "Larian Triangle", situated between the two southern branches of the Como Lake (Lombardy - northern Italy) (Fig. 1).
As for caves, this is one of the richest areas in Lombardy. Karst is much more developed on the slopes draining towards the western branch of the lake, whose cross-valleys are deeply embanked and connected to the lake by deep gorges, continuing under the lake level (Bini, 1994).
The study takes into consideration one of these cross-valleys, the ESE-WNW trending Valle del Nosê, which drains its water westward: one of the most important Lombard karst system is situated in this valley (Bini & Vanin, 1974; Bini & Pellegrini, 1979; Maggi, 1982; Tognini, 1993, Tognini, 1994; Ferrari & Tognini, 2000) (Fig. 2).

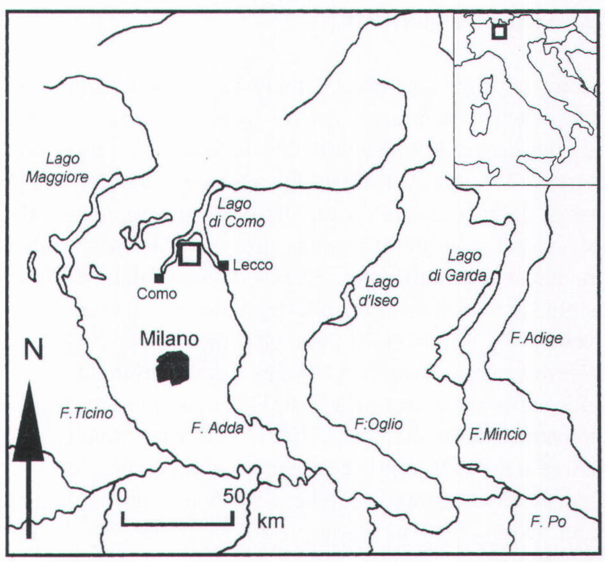

Figure 1. Geographical setting of the study area.

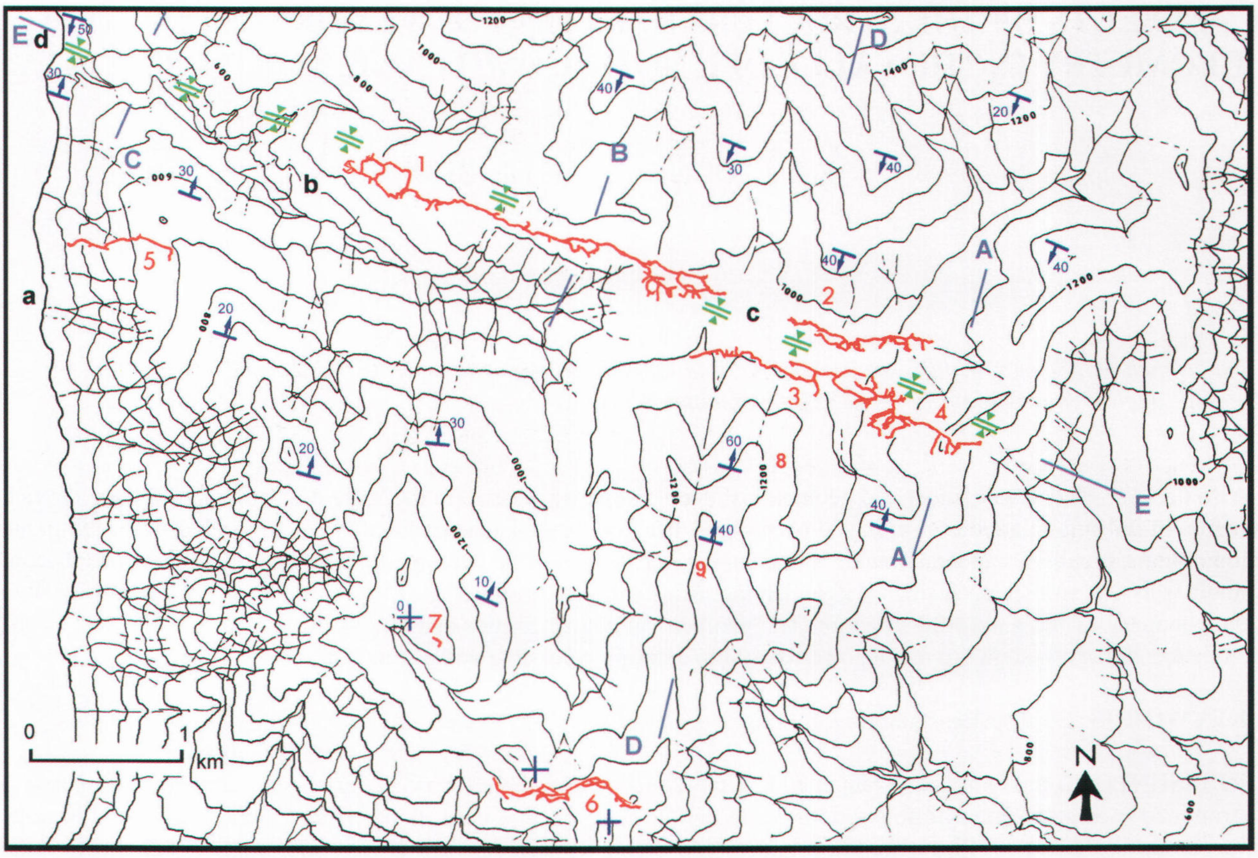

Figure 2. Schematic map of the area, with the plan views of the main caves (in red) and the main syncline axis (in green).
a – Como Lake **b** - Nosê Valley **c** - Pian del Tivano **d** - Main springs of the karst system

Main syncline axis Bedding dip direction

Main caves plan views (in red): **1** - Tacchi-Zelbio System **2** - Bus de la Niccolina **3** - Grotta Stoppani **4** - Abisso Cippei **5** - Grotta Masera **6** - Bul-Guglielmo System **7** – Grotta Como **8** – Abisso della Betulla **9** – Bus de Colma Squarada
A – Cross section on Fig. 6A **B** – Cross section on Fig. 6B **C** – Cross section on Fig. 6C
D – Cross section on Fig. 10a and 10b **E** – Longitudinal section on Fig. 9a and 9b

2. Aim of the study

After a simple, summary analysis, the Valle del Nosê endokarst system proves to be deeply influenced, as for its geometric arrangement, by the main structural features of the area. The aim of this paper is a detailed analysis of the relations of the endokarst arrangement with the structural setting in the study area, in order to corroborate in a quantitative manner, based on field data, the first-sight karst/structure dependency deduced after caves surveys (Tognini, 1994; Tognini & Bini, 1998).
For this purpose, over 6300 joints were measured both inside caves and at the surface. 4000 of these joints were systematically measured in 40 sites (20 of them located inside caves at different depths): for each site, 100 joints were systematically measured, together with their frequency, length and width, opening, fillings, tectoglyphs, etc.. Over 1150 bedding planes were measured, scattered all over the area (Tognini, 1994; Tognini & Bini, 1998). The mean fold axis trend and plunge were derived from the *eigenvectors* method (Cheeney, 1983), and then compared with 200 minor fold axis measured in the field: field data fit very well with the *eigenvectors* method (Tognini, 1994).
A detailed analysis of cave surveys allowed the whole 30 km-long system to be divided into 2425 portions of galleries (Tognini, 1994; Tognini & Bini, 1998): each portion is a rectilinear gallery or passage, characterised by its trend, plunge and length and by a morphological uniformity, which make every portion different from the other ones: every change in one of the geometrical or morphological parameters creates a separate portion (Jaskolla & Volk, 1986).
Lower-hemisphere equal-area stereographic projections for all these data were subsequently compared one another (Tognini, 1994), in order to point out the dependency and relationship of bedding and jointing with the geometric arrangement of the endokarst system (Kiraly, 1968, 1969b; Kiraly *et al.*, 1971;.Jaskolla & Volk, 1986).

3. Structural-geological setting

In this area only the Moltrasio Limestone Formation crops out, Jurassic in age (early Lias), a monotonous sequence of marly, dark-coloured limestones with chert nodules and bands in a variable quantity; this limestone exhibits well defined, 30-80 cm thick beds, with marly-clayey, few centimetre thick interbeds (Rossi *et al.*, 1991a, 1991b). A peculiar character of the Moltrasio Limestone in this area is the occurrence of several levels affected with slumping, in 50-100 cm up to 10-15 m thick layers, mainly confined in a narrow WNW-ESE trending zone almost parallel to the valley and to the syncline axis. These features proved to have a great influence on karst voids development: the occurrence of huge hypogean rooms is in this area always related to thick slumped layers (Tognini, 1994; Tognini, 1998; Tognini, 2000).

The area is affected by a km-scaled synclinal structure, (Fig. 2 & 3A-B) whose fold axis trends N120°E plunging 10-20° to ESE (Maggi, 1982; Bini *et al.*, 1985; Gaetani & Bini, 1990; Tognini, 1994; Tognini & Bini, 1998; Ferrari & Tognini, 2000). Bedding planes poles show a girdle distribution with a sharp bimodal clustering (Fig. 4).

Coaxial metric secondary folds are associated with the syncline in a belt mainly confined close to the hinge zone of the main fold. As previously said, the minor fold axis measured in the field (Fig. 5) fit well with the theoretical fold axis derived from *eigenvectors* method, which was easy to calculate thanks to the bimodal distribution of bedding planes poles (Cheeney, 1983).

To the NE, the structure evolves into a monocline cut by valleys entrenchment, causing the cropping out of the basal facies of the Moltrasio Limestone and of the underlying formations; further to the North, the synclinal structure is overthrusted by older formations, while to the S it evolves into an anticline overthrusting younger formations (Jadoul & Rossi, 1982; Bernoulli *et al.*, 1990; Gaetani & Bini, 1990; Bertotti, 1991) (Figs. 3A-B); to the W the fold structure dips under lake level and it is thought to continue on the other side of the western branch of the lake, but correlation of folded structures on opposite lake shores is difficult because of later N-S transcurrent tectonics affecting the area to the West (Rossi *et al.*, 1991a).

To the E the hinge zone is very broad and poorly defined, displaying intense secondary folding, while to the W it is much more marked and narrow, with no secondary folds, getting narrower approaching the lake shore, where it is just a few tenths of meter wide (Tognini, 1994) (Fig. 6).

A structural analysis deep into the endokarst (Figs. 7B & 10B) allowed to prove that minor folds tend to grow gentler and wider the deeper one gets into the structure, their wavelength increasing and their amplitude decreasing till they gradually die out. So, while at the surface the hinge zone is very broad and poorly outlined, deep in the structure it could be restricted to a narrow zone around a hypothetical axial surface: close to the surface, caves seem to be placed in the hinge zone, but at depth endokarst is clearly developed in the southern limb of the main syncline, though very close to the hinge zone, (but it must be taken in mind that the presently explored karst system is just a small, fragmentary portion of a much larger unknown karst network: since geological setting, as for lithology and jointing, is symmetric with respect to the fold axis, we infer a similar karst system must exist in the northern limb of the main fold, but it is actually still to be explored).

The general structure of the main fold is created by tangential longitudinal strain, thus strain is mainly accomodated in the hinge zone (Ramsay & Huber, 1987). A neutral surface separating an upper compressional zone and a lower extensional zone (where endokarst is much more probable to occur thanks to pre-karstic higher permeability) is thus to be expected. The structure of the main fold is actually complicated by the occurrence of minor folding, which makes strain accomodation much more complicated and creates a waving, folded neutral surface. Furthermore, the presence of marly-clayey, a few centimetre thick interbeds, along which bed-on-bed slipping and sliding occur, creates a sort of "disengagement" between layers in the structure (Fig. 7B). This is observed at different scales: minor slipping is observed along one single bed, or it involves piling of 3-4 layers; after the observation of minor folds geometry and of frequency of particularly thick and plastic clayey layers, remarkable slipping must be inferred to occur between layers up to several tenths of meter thick. A considerable portion of the strain is therefore accomodated also by slipping and gliding along bedding planes, thus involving the limb zones in the deformation, as it is proved by observed tectogliphs on bedding planes, such as *striae* and fibrous calcite growth, extensional sigmoidal veins and small-scale deformation, such as small drag folds, shear cleveage and saddle reef, in the clayey interbeds.

In this situation, each single bed, or piling of "engaged" beds is folded by buckling, with tangential longitudinal strain accomodation in the hinge zone, and is therefore subjected to a compressive stress field in its inner core portions and to extensional condition in its outer portions, but at the same time it is free to slip along under- and over-lying beds (Fig.7A): this creates a multilayer structure, with an alternation of compressed zones (and therefore virtually impervious and not karstifiable) and extended zones (joint-pervious and thus allowing cave development) (Fig.7B).

Such a geometry of the fold structure is of basic consequence as for the main features and geometrical arrangement of the Valle del Nosê karst system, as it will be explained in the next chapter (Tognini, 1994; Tognini & Bini, 1998).

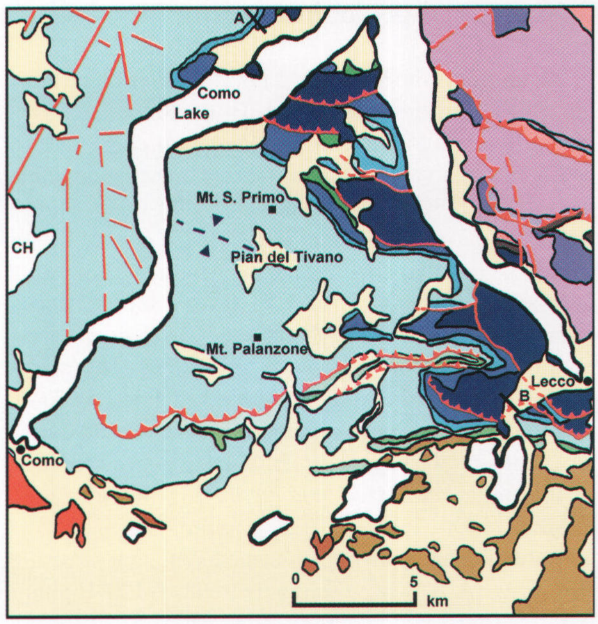

Figure 3A. Schematic geological map of the southern portion of the Como Lake district

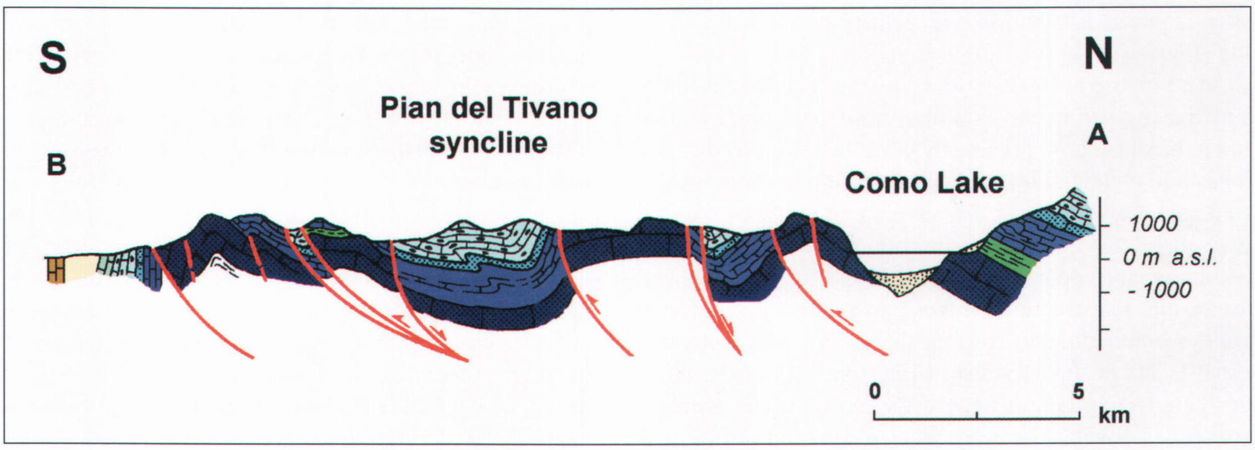

Figure 3B. Schematic geological cross section of the southern portion of the Como Lake district (after Gaetani & Bini, 1990)

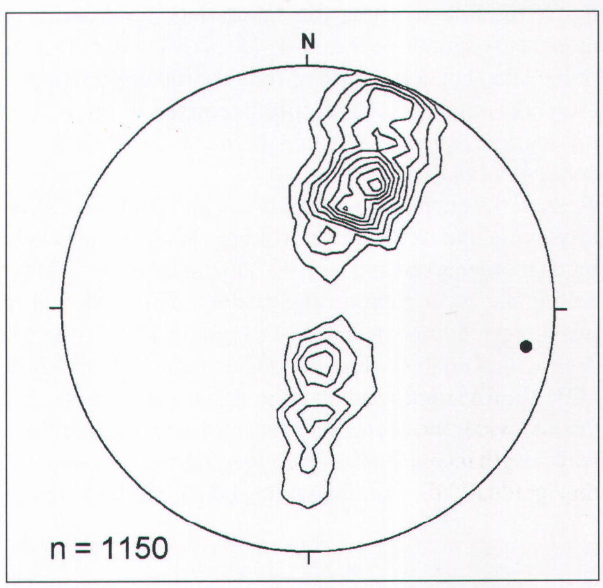

Figure 4. Lower-hemisphere equal-area stereographic isodensity contour lines projection for bedding planes in the study area. The black circle represents the mean fold axis as deduced from *eigenvectors* method.

Servino: marine transgressive shallow water siltstones, sandstones and limestones (Scythian)
Calcare di Prezzo and Calcare di Angolo: shallow water limestones (Anisian)

Calcare di Esino: carbonate reef and back reef limestones and dolomitic limestones (Ladinian)

Wengen and Buchenstein Formations: intraplatform basin limestones and sandstones (Ladinian)

Gorno Formation. and Calcare Metallifero Bergamasco: shallow water limestones, claystones and sandstones (early-middle Carnian)

San Giovanni Bianco Formation: alluvial and peritidal claystones, limestones and evaporites (late Carnian)

Dolomia Principale: marine transgressive carbonate platform dolomites (Norian)

Argilliti di Riva di Solto: intraplatform basin claystones (Rethian)

Calcare di Zu: intraplatform basin limestones (Rethian)

Dolomia a Conchodon: shallow water limestones and dolomitic limestones (late Rethian–early Lias)

Calcare di Moltrasio: deep basin silica-rich limestones (Hettangian–Domerian)

Selcifero Lombardo: deep water silica-rich marly limestones and cherts (late Callovian–Tithonian)

Maiolica: deep water silica-rich limestones (Tithonian–Barremian)

Scaglia Lombarda: deep water silica-rich marls and limestones (late Barremian–middle Eocene)

Flysch di Bergamo: turbiditic sandstones, claystones and conglomerates (Turonian)

Gonfolite Lombarda (Southalpine Molasse): turbiditic sandstones and conglomerates (late Oligocene-Burdigalian)

Quaternary deposits

main faults

main thrust faults

Valle del Nosê sinclyne

Legend figure 3

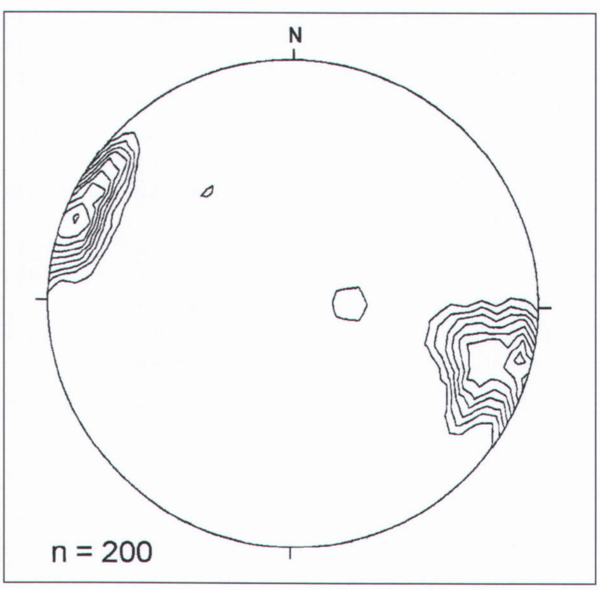

Figure 5. Lower-hemisphere equal-area stereographic isodensity contour lines projection for minor fold axis measured in the field.

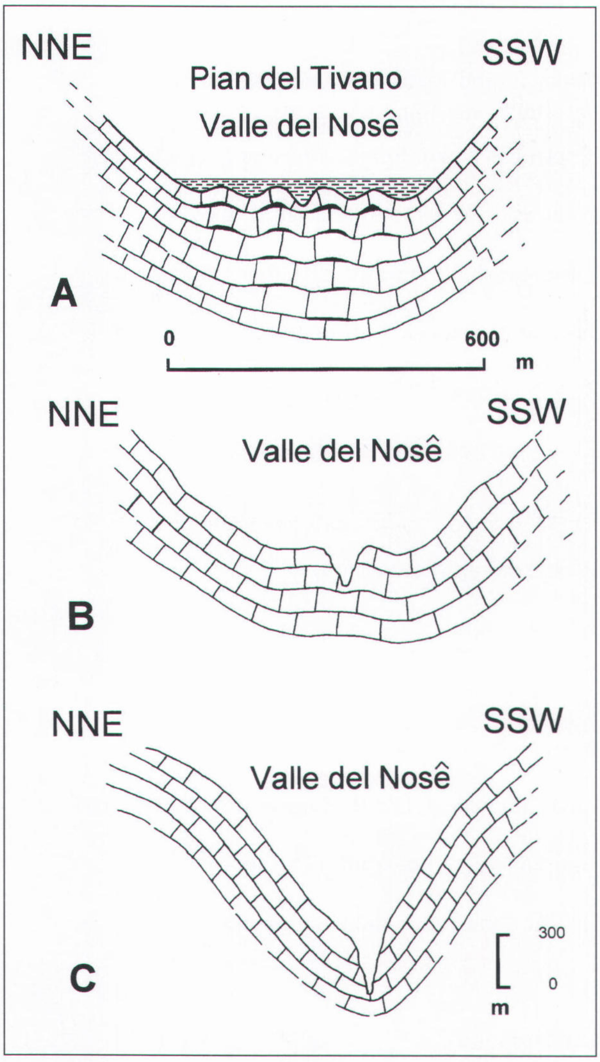

Figure 6. Schematic cross-sections across the main synclinal structure, from ESE (**A**) to WNW (**C**), showing its hinge zone, very wide and complex in the ESE portions, gets simpler and narrower approaching the lake shore, where it is just a few tenths of meters wide (not in scale: scale bar is only indicative).

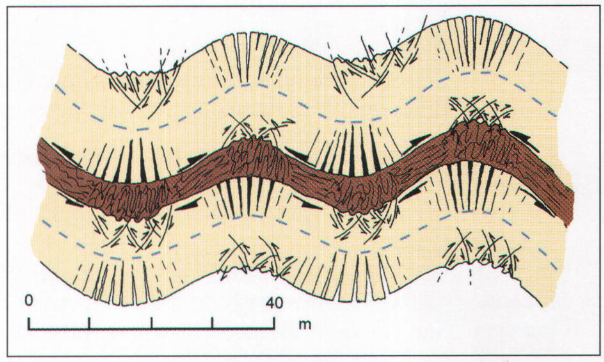

Figure 7A. Schematic folding of parallel layers separated and "disengaged" by a plastic clayey interbedding: strain is mainly accomodated in the hinge zone (tangential longitudinal strain), creating a neutral surface (in blue) separating compressional and extentional zones, but considerable slipping and deformation may occur in the plastic layers.

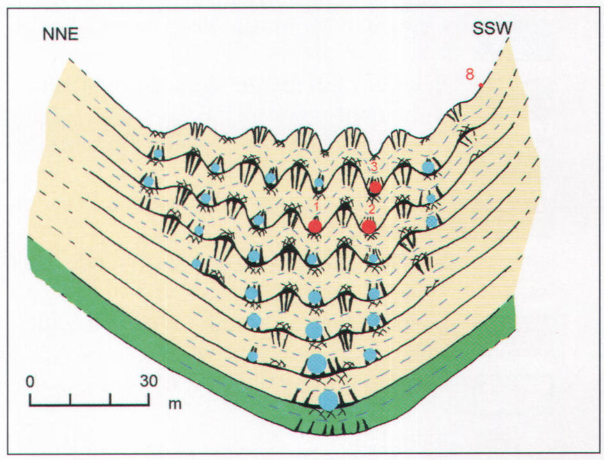

Figure 7B. Schematic structure of the main fold, with related minor folds. Karst voids tend to develop in the extensional zones, where joint opening is greater, the compressional zones are virtually impervious, thus unkarstifiable, and the neutral surfaces (in blue) in the fold structure therefore act as impervious barriers to karst processes. The multilayer geometry of the fold structure strictly controls the distribution and geometry of karst voids, which develop parallel to the main synclinal axis on different levels poorly interconnected one another, in a multilayer configuration mimicking the fold structure geometry.
Red circles mark the position of presently known caves in this section
1 - Tacchi Zelbio system, **2** - Bus de la Niccolina, **3** - Grotta Stoppani, **8** – Abisso della Betulla
Light blue circles mark the hypothetical position of still unknown galleries, which are supposed to form in the extentional zones of the structure associated with minor folding.
In green the underlying poorly karstifiable Dolomia a Conchodon Formation (whose position is uncertain).

The area is characterised by significant brittle tectonics, related to the main fold structure. After the analysis of the total lower-hemisphere equal-area stereographic projection of the discontinuities (Fig. 8), the area is deduced to be characterised by two main sets of joints: a longitudinal set and a transverse one, together with three oblique sets, which are otherwise less numerous and less meaningful as for karst system development (Tognini, 1994; Tognini & Bini, 1998).

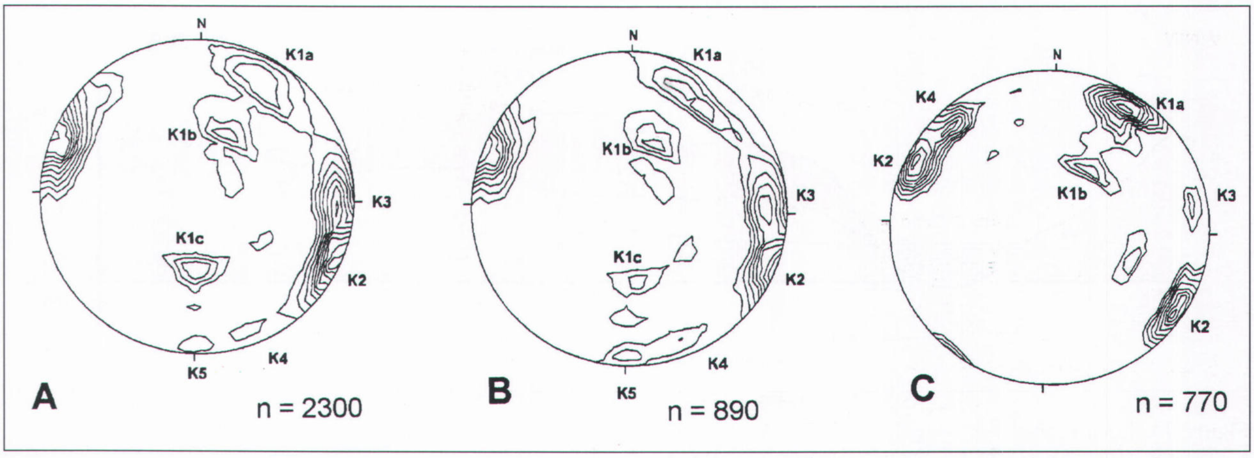

Figure 8. Lower-hemisphere equal-area stereographic isodensity contour lines projection for:
A - main joints sets in the whole study area: note sets K_1 (divided into 3 sub-sets with different dipping angles), K_2 and K_3 are the most diffuse sets;
B – main joints sets in the hinge zone;
C – main joints sets in the southern limb of the structure.

The longitudinal set (K_1) is 110-120° N striking, parallel to the fold axis and perpendicular to bedding; it can be divided into three sub-sets on the basis of dipping:
K_{1a} - subvertical set, mainly occurring in the axial zone
K_{1b} - westward dipping, mainly occurring in the southern limb, with dipping angle decreasing from subvertical in the axial zone to 30-40° in the marginal areas (1-2 km away from the hinge zone).
K_{1c} - eastward dipping, mainly occurring in the northern limb, with dipping angle decreasing from subvertical in the axial zone to 30-40° in the marginal areas (1-2 km away from the hinge zone).
The whole K_1 population is distributed on a great circle with the fold axis as its pole.
Metric-decametric joints are mainly subvertical in the axial zone, but minor, locally intense metric-decimetric jointing may show E or W-ward dipping with variable angles associated with minor metric folding.
The transverse set (K_2), perpendicular to the main fold axis, is 20-30° N striking, mainly vertical, with minor dipping sub-sets.
Three other sets are present, though much less abundant:
one N-S striking, subvertical set (K_3);
one 50-60° N striking, subvertical set (K_4);
K_3 and K_4 may possibly represent a conjugate set related to the main fold structure or be independent: no sure field evidence can corroborate any hypothesis;
one E-W striking, subvertical set (K_5), which seems to be independent with respect to the fold structure.

4. The endokarst system

The Valle del Nosê hydrogeological basin is characterised by an endokarst organised in a system of caves with a total length of about 30 km (Bini & Vanin; 1974, Bini & Pellegrini, 1979; Maggi, 1982; Tognini; 1994; Ferrari & Tognini, 2000) (Fig. 2; Figs. 9A-B; Fig. 10A).
The deepest cave is Abisso di Monte Bul (-560 m), but the difference in height between catchment area and springs exceeds 1400 m: karst potential is even higher, being the main springs of the system situated under the lake level, probably at the contact of the Moltrasio Limestone with the less karstifiable underlying Dolomia a Conchodon Formations (Bini *et al.*, 1985; Bini, 1994) (Fig. 9A), whose precise position is presently unknown, but is estimated to be some tenths of meter below lake level.
The Valle del Nosê karst system is made with two lateral deep vertical caves and 6 main caves in the southern limb of the fold, very close to the hinge zone (Fig. 2; 9A-B; 10A) (Ferrari & Tognini, 2000). Besides these main caves, some small minor caves are known in the northern limb, probably belonging to a hypothetical, still unexplored system, which is supposed to exist and be symmetric to the one located in the southern limb: the presence of this unknown system is inferred both on the basis of the geological and structural analysis (Fig. 7B) (lithological and jointing setting are similar, and symmetric, with respect to the main fold axis) and by the occurrence of some important karst springs of unknown origin (Maggi, 1982; Bini *et al.*, 1985; Tognini, 1994; Tognini & Bini, 1998).

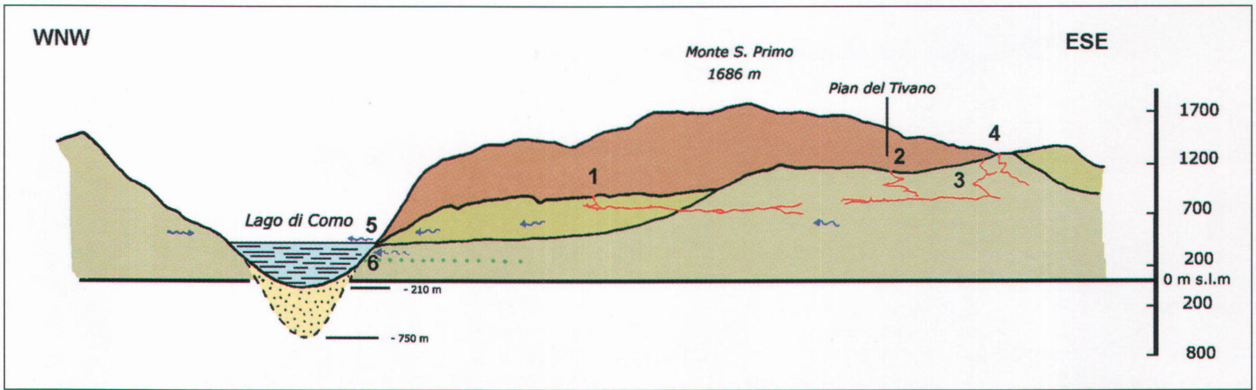

Figure 9A. Longitudinal section with the profile view of the main caves.
1 - Tacchi- Zelbio system **2** - Bus de la Niccolina **3** - Grotta Stoppani
4 - Abisso Cippei **5** - Main springs of the system **6** - Hypothetical springs under the lake level
Blue arrows: hypothetical underground water pathway to the springs
Green dotted line: hypothetical contact of the Moltrasio Limestone with the underlying Dolomia a Conchodon Formation

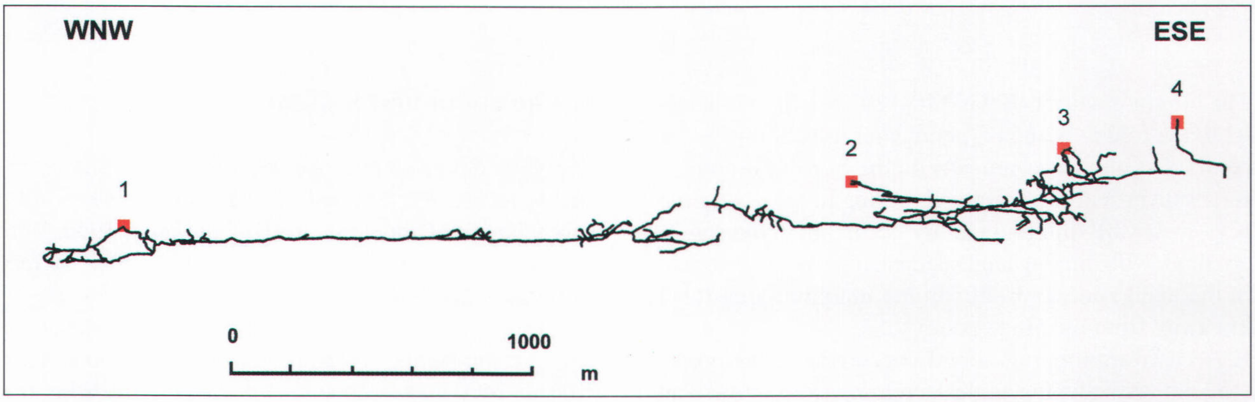

Figure 9B. Longitudinal profile view of the main caves of the area, projected on a WNW-ESE vertical plane.
1 – Tacchi- Zelbio System **2** – Bus de la Niccolina
3 - Grotta Stoppani
4 – Abisso Cippei Caves entrance in red.

4.1. Endokarst-jointing relation

All caves show a strong dependency on structure, particularly on bedding and jointing. The analysis of the lower-hemisphere equal-area stereographic projections (Kiraly, 1968, 1969b; Kiraly *et al.*, 1971; Jaskolla & Volk, 1986; Donini, 1987; Tognini, 1994) of the main joint sets, bedding planes and directions of karst galleries (Figs. 11; 12; 13; 14) shows the latter tend to develop following the intersection of bedding planes and one of the main sets of joints, mainly the longitudinal set or the transverse one.

The longitudinal system K_1, made with subvertical or steeply dipping discontinuities, with a 110-130° N direction, allows the genesis of sub-horizontal galleries, mainly of great size, parallel both to the synclinal axis and to bedding direction: these galleries are therefore prone to drain underground water towards the lake (Fig. 2; Figs. 9A-B). They exhibit rectangular cross-sections, typically wide and low; sometimes they may preserve syngenetic morphologies with elliptical cross-sections, but breakdown processes often erase all predating morphologies.

The transverse system K_2, represented by vertical discontinuities, with a 20-30° N direction, allows the development of steep galleries perpendicular to the synclinal axis, along intersections with bedding planes, parallel to bedding dip, and is therefore prone to drain water towards the main drains of the hinge zone of the syncline (Figs. 10A-B). These galleries exhibit rectangular cross-sections, typically very high and narrow, with vertical straight walls.

All other joint sets cause the development of short, sometimes numerous but usually narrow galleries, numerically meaningless with respect to the galleries parallel to the longitudinal and transverse joint sets. The only exception is the K_3 set, which may sometime create important galleries.

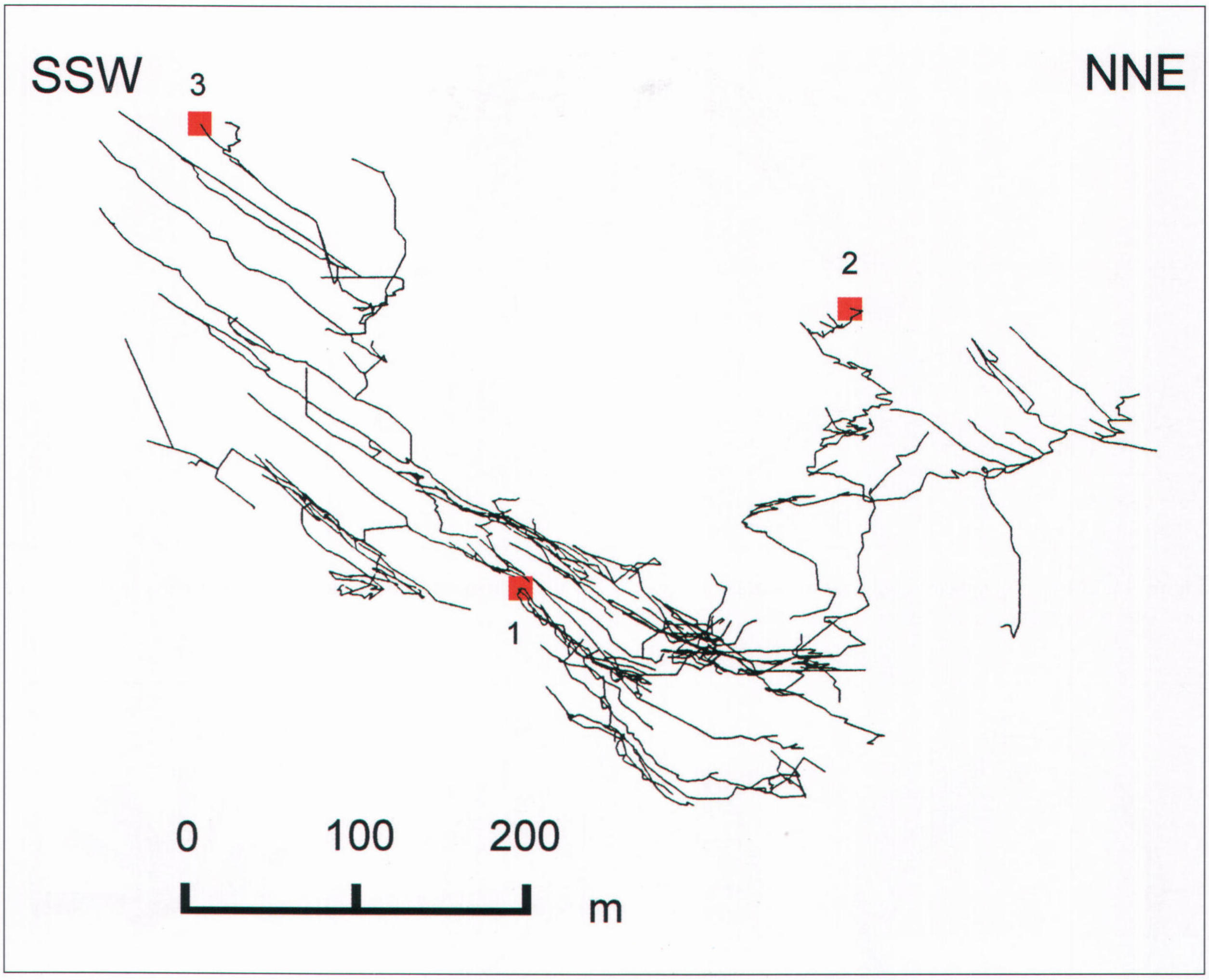

Figure 10A. Cross-section profile view of the main caves of the area, projected on a NE-SW vertical plane.
1 – Tacchi- Zelbio System **2** – Bus de la Niccolina **3** - Grotta Stoppani
Caves entrance in red.

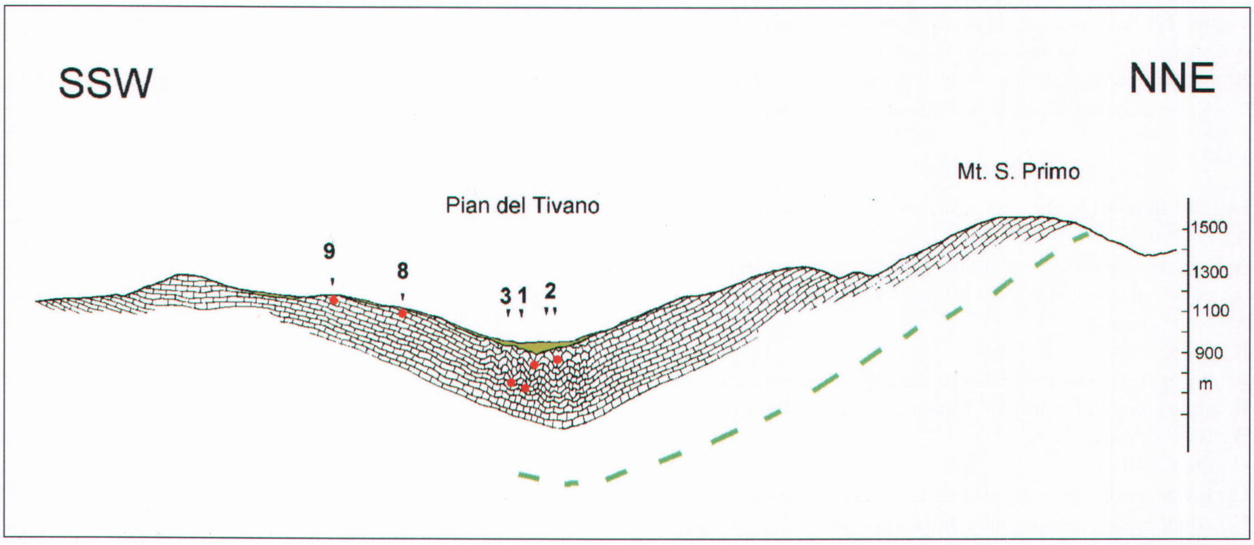

Figure 10B. Cross section of the main fold structure with positions of the main caves
1 - Tacchi-Zelbio System **2** - Bus de la Niccolina **3** - Grotta Stoppani **8** – Abisso della Betulla **9** – Bus de Colma Squarada
In green: contact of the Moltrasio Limestone with the Dolomia a Conchodon Formation (uncertain).

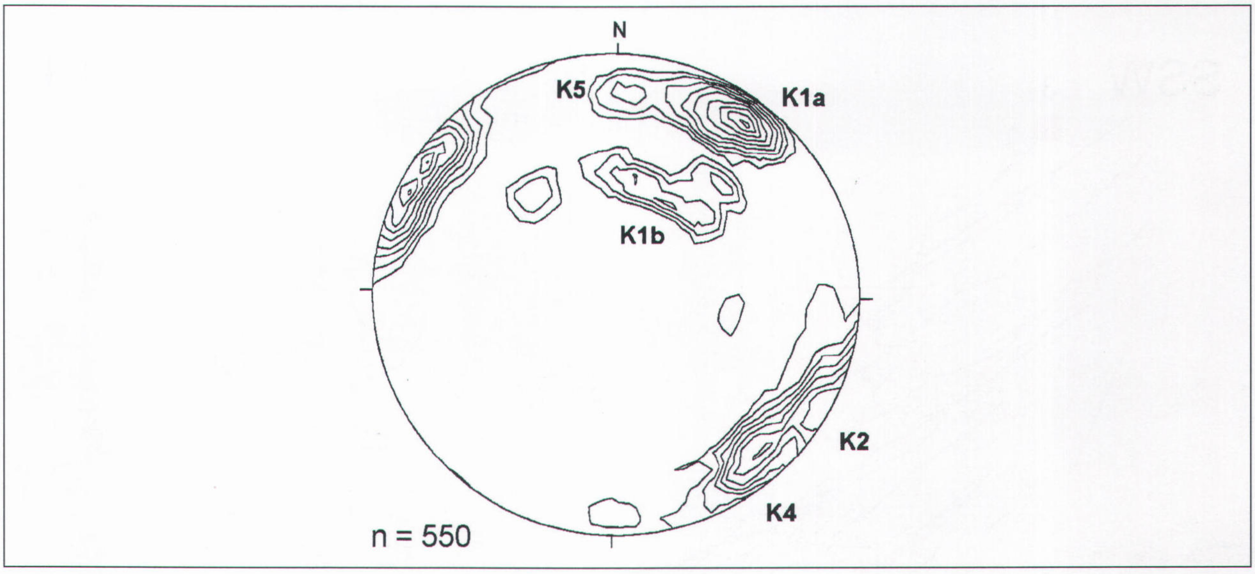

Figure 11. Lower-hemisphere equal-area stereographic isodensity contour lines projection for main joints sets poles in the example cave Grotta Stoppani.

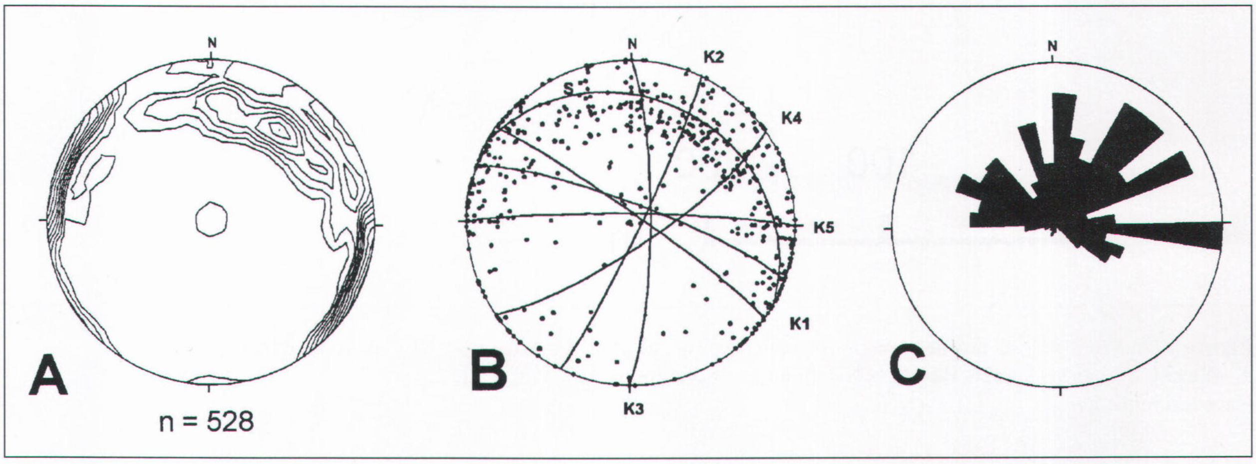

Figure 12. Lower-hemisphere equal-area stereographic projections for the 528 galleries measured in the Grotta Stoppani:
A – isodensity contour lines projection
B – projection of galleries (black points) with bedding planes (S) and mean main joint sets.
C – Rose diagram showing the existence of 3-4 prevailing directions for galleries.

Legend figure 13. The 528 galleries in Grotta Stoppani were grouped in 4 classes, on the basis of their length L.

A - L< 5 m
A_1: lower-hemisphere equal-area stereographic projection for galleries with L<5m
A_2: equal-area stereographic isodensity contour lines projection
A_3: Rose diagram
B - 5<L<20 m
B_1: lower-hemisphere equal-area stereographic projection for galleries with 5<L<20m
B_2: equal-area stereographic isodensity contour lines projection
B_3: Rose diagram
C - 20<L<40 m
C_1: lower-hemisphere equal-area stereographic projection for galleries with 20<L<40m
C_2: equal-area stereographic isodensity contour lines projection
C_3: Rose diagram
D - L>40 m
D_1: lower-hemisphere equal-area stereographic projection for galleries with L>40m
D_3: Rose diagram

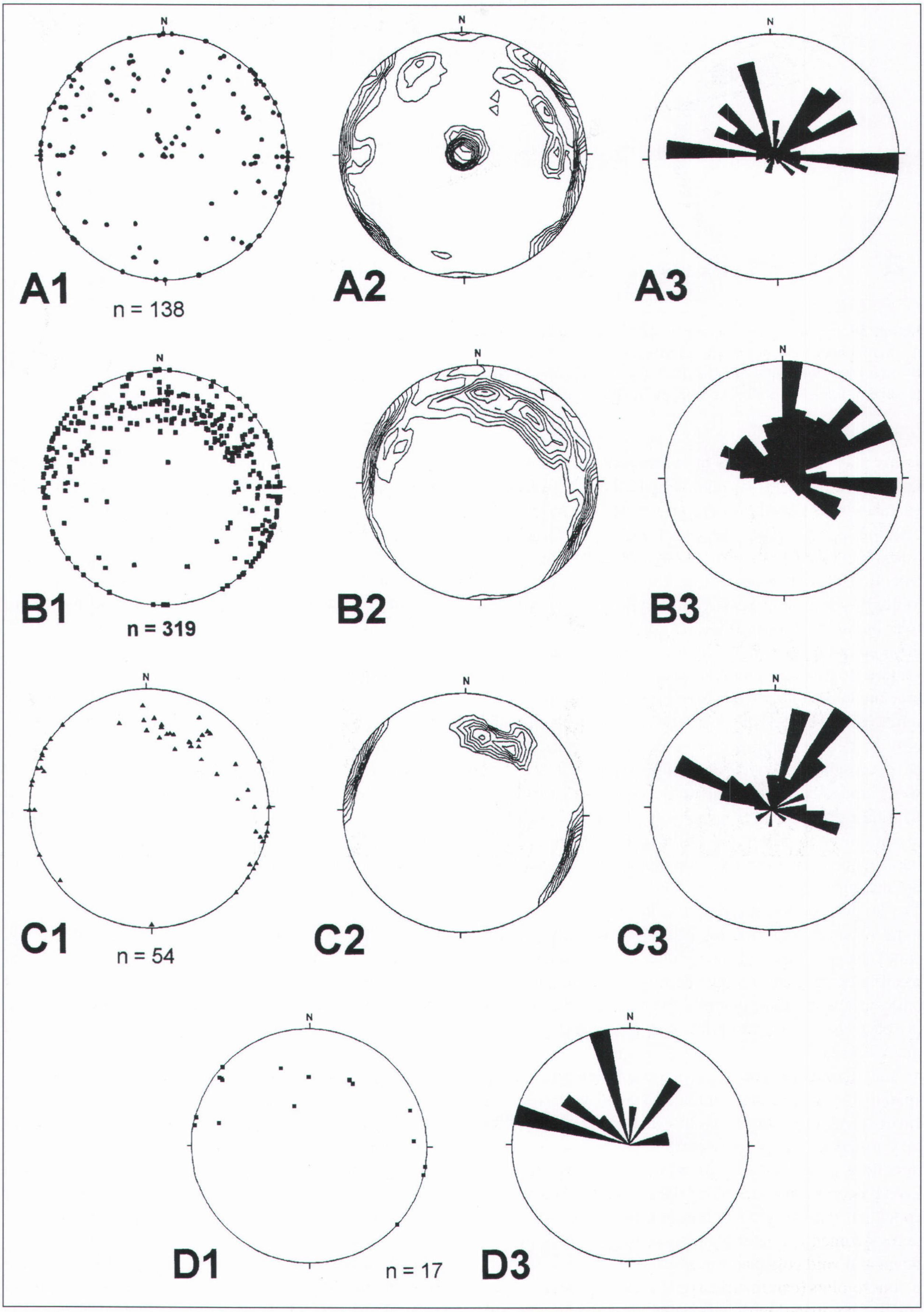

Figure 13.

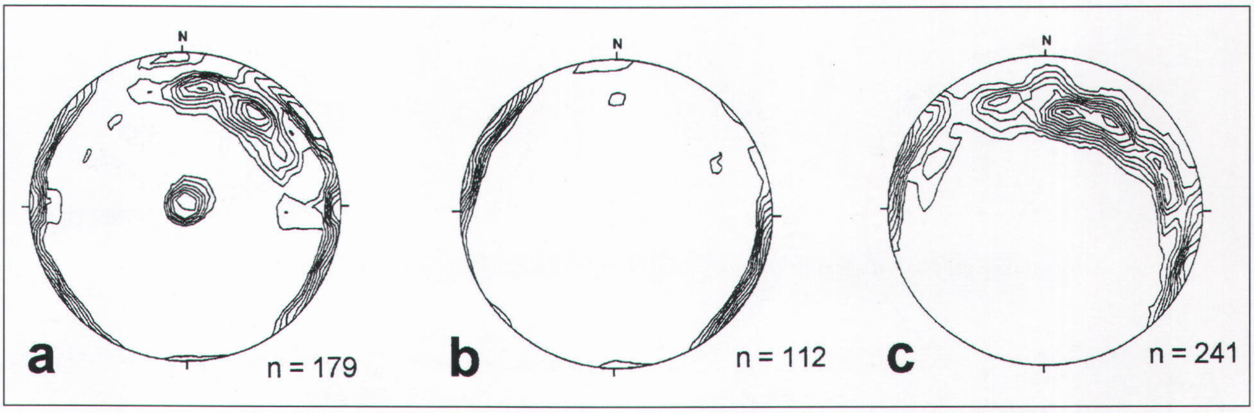

Figure 14. Lower-hemisphere equal area stereographic isodensity contour lines projection for:
A - main upper branches of Grotta Stoppani
B - main sub-horizontal drain zone of Grotta Stoppani (the deepest portion of the cave)
C - lateral branches of Grotta Stoppani feeding the main drain zone

Joints play different roles in controlling karst distribution, depending on their relative spatial dimensions and characteristics (length, width, surface area and roughness, opening, etc..), on their frequency and on their intersections with other joint sets (Kiraly, 1968, 1969a; 1975; Boegli, 1980). The most important characteristics for joints in controlling karst geometry and directions are their initial opening and their length (or, better, their spatial continuity, for which length is one of the most representative parameters, and the easiest to measure and appreciate in the field): since original opening of karstified joints cannot be measured or estimated anymore, it may only be deduced that the most karstified joints should have been the most wide-opened in origin, and that they were more favourably oriented with respect to initial hydraulic gradients: it is easy to infer that initial pre-karst discontinuities openings must be at their widest at the intersection of two, or more, discontinuities sets (jointing or bedding).

The longest and most continuos discontinuities are the more favourable to form long galleries, thus controlling endokarst geometry and underground drainage directions: the role of bedding in controlling karst arrangement is basic because bedding planes are very long and continuos in space. As for length, joints can be divided into two main classes:

a - macrojoints (metric to decametric in length), whose spatial dimensions are comparable with galleries and caves passages width, span and length: they proved to play a major role in controlling underground drainage directions in the first karstification phases, thus guiding karst processes and controlling the geometry of the whole endokarst system, and in addition they control cave passages geometry in later phases, controlling rock breakdown and void collapse processes;

b - microjoints (centimetric to decimetric in length), very small if compared with karst voids dimensions, control the permeability of unkarstified (or less karstified) blocks feeding the main karstic drainage pathways, so that they play a major role in supplying karst with water, but they seem to have no significant role on karst 3-dimensional arrangement and on karst morphologies.

This is the reason why the longest and widest galleries developed along the longitudinal joint set, which is actually the one which exhibits the longest and most continuous jointing.

An example case: Grotta Stoppani

As an example for all caves in the area, we can consider the field data of Grotta Stoppani. The relations of karst system arrangement and structural setting are very well pointed out in this caves, though all caves in the area have the same arrangement (Tognini, 1994; Tognini & Bini, 1998).

The lower-hemisphere equal-area stereographic projection of main joint sets (Fig. 11) measured in the cave shows the occurrence of 5 main joint sets, but 3–4 of them are prevailing in number and frequency of jointing. These are the same joint sets found at the surface all over the area (Fig. 8C; Fig. 11), with K_1 set (longitudinal joints) showing typical vertical and SW dipping joints, as it usually happens in the southern limb of the main synclinal structure.

A comparison of joints measured at the surface and inside all the caves of the system points out that there is no significant difference in jointing: the same sets are found at the surface and at depth, with the same strike and dip, similar length, continuity and frequency: one of the most interesting point is that opening of unkarstified discontinuities is the same inside caves and at the surface, so that it can be deduced that in karst areas discontinuities do not tend to be subjected to any closure with depth, thanks to the presence of large size underground voids which cause tensional release phenomena in their neighbourhood (Tognini, 1994).

At the surface (Fig. 2) the cave seems to be situated in the hinge zone, because the latter is very wide and complex thanks to minor folding, but at depth, where the hinge zone is narrower and with no minor folding (Fig. 7B; Fig. 10B), it is clearly developed in the southern limb, as also shown by a projected cross section of the caves system, transverse with respect to the main fold axis, where it is possible to appreciate many parallel branches are regularly developed along bedding planes dip (Fig.10A). The cave is about 7200 m long and 330 m deep: its whole length was divided into 528 segments with homogeneous trend and plunge (Fig. 12A).

The lower-hemisphere equal-area stereographic projections of the galleries directions (Fig.12B) clearly show most galleries are scattered along the cyclographic arc representing the mean bedding plane, with clustering at the intersection of bedding planes with the cyclographic arc representing the mean main joint sets , as deduced after Fig. 11.

Karstologists often use rose diagrams for comparing jointing and galleries directions, but the use of stereographic projections is in this case much more useful and is therefore recommended: note the use of rose diagrams gives no information about plunges of galleries and cannot help in pointing out the actual relations of galleries and discontinuities: it is not possible to find out that galleries do not form along a unique surface (a bedding plane **or** a joint), but they do form at the intersection of two different planes (a bedding plane **and** a joint). With the use of rose diagrams alone, the role of discontinuities may be misunderstood, especially in the case these two planes have the same strike, as it is the case for bedding planes and the longitudinal joint set.

If we group all the 528 galleries as for their length, we notice that:

a - galleries with length L< 5 m are scattered all over the diagram (Fig. 13A), although a certain clustering at the intersection of main joint sets with bedding planes is evident.

b - galleries with length L 5<L<20 m (which are the most relevant in number, being 319 on a total of 528) show a distribution perfectly fitting the main bedding plane cyclographic arc (Fig. 13B), with dense clustering at the intersection with K_1, K_2, K_3, K_4, K_5 families, with a major clustering for K_1, K_2 and K_3 joint sets.

c – for galleries with length 20<L<40 m (there are 54 of them), the clustering of directions at the intersection of bedding plane with K_1, K_2, K_3 joint sets is even more evident (Fig. 13C), and the same trend is shown by galleries with length L>40 m (Fig. 13D).

While the role of bedding planes in guiding karst galleries is the same regardless of bedding strike and dip and whatever joint set is used for developing galleries, the distribution of joint-guided galleries is not homogeneous all over the cave: the latter can be divided into 3 main portions, where different morphologies and geometric arrangement occur:

In the upper branches (Figs. 9B, Fig. 10A), characterised with short and narrow galleries with a vertical trend (with the occurrence of shafts) and a labyrinthine arrangement, galleries are developed at the intersection of bedding planes with all the main joint sets (Fig. 14A); jointing is intense, but discontinuities are short, thanks to intense minor folding. We may think in this portion of the system all joint sets played a similar role in the genesis and evolution of karst galleries, that is to say they were equivalent as for their hydrogeological parameters and characteristics.

Deep in the cave (and deep in the syncline core), the cave is characterised with large, long, sub-horizontal drains, often parallel one to the others (Fig. 2; Figs. 9A-B), with a marked longitudinal trend (Fig. 14B), with very few galleries escaping this scheme.

The main drain galleries are fed by long lateral straight branches (Fig. 10A), characterised with steep galleries (but no vertical shafts) at the intersection of bedding planes with transverse K_2 and K_3 joint sets, together with shorter longitudinal trending galleries (Fig. 14C). The plunge of the galleries is the same of bedding planes.

4.2. Endokarst-structure relation

One of the most peculiar features of the Valle del Nosê endokarst arrangement is that longitudinal galleries occur at different depths, and that they are parallel one to the others, in a sort of "multilayers" arrangement(Fig. 9B; Fig. 10A). It must be pointed out that vertical spacing between different levels of longitudinal galleries is generally some tenths of meter, just the same as "disengaged" layers thickness in the fold structure.

Every folded layer in the multilayer structure of the fold has an inner compressed zone and an outer extended one (Fig. 7A), each characterised with different jointing arrangement leading to different permeability and different karstifiability (Tognini, 1994; Tognini & Bini, 1998). The extensional zones of each layer are the most favourable zones for endokarst voids to form, and the longest and largest galleries are usually found there: the extensional zones are favourable to the development of sub-horizontal, linear galleries (parallel to the syncline axis), having the hydraulic function of main drains (it must be pointed out that most of the world longest and most complex cave systems are formed in a synclinal structure, where bedding dip is favourable to drain water toward the extensional zone at depth, while in anticlinal structures underground water is drained away from the extended zone). The compressed zones are on the contrary impervious and thus unkarstifiable. The neutral surface separating the two portions acts indeed as an impervious barrier to karstification, separating karstifiable zones in the extended portions and unkarstifiable zones in the compressed portions.

We may think the main drain zone of the Grotta Stoppani is located in one of these extension zones, characterised with long and continuos opened jointing (which is actually observed in the field), while the labyrinthine portion may be located in an intermediate zone, affected with intense, but less continuos jointing (also observed in the field), possibly confined at its top by a compressed, not permeable zone (which cannot be observed because no karst voids are found there).

This occurs in all the caves of the area, so that systems of multilevel parallel galleries are therefore formed (Fig. 2; Figs. 7B; Figs. 9A-B; Figs. 10A-B): they are connected one another by sets of vertical discontinuities (mainly, the transverse joint set), which create casual connections between the different horizontally-draining levels.

Minor folding distribution controls the distribution of extensional, karstifiable zones, so that the main horizontal drains become larger the deeper they are, and their number gradually reduces with the minor folding dying out, till they will form an hypothetical, still unexplored unique drain in the outer and deeper part of the axial zone, probably at the contact with the underlying Dolomia a Conchodon Formation (Fig. 7B) (Bini *et al.*, 1985; Gaetani & Bini, 1990; Tognini, 1994; Tognini & Bini, 1998).

The relationship of bedding and jointing with endokarst is so strict that the multilayers structure of the fold causes a multilayer structure of the karst system. Such a model is of basic consequence as for the characteristics of the Valle del Nosê endokarst system, which actually exhibits long straight galleries, parallel one to the others, at different structural levels (Fig. 2; Figs. 7B; Figs. 9A-B; Figs. 10A-B).

Since the 60th's, cavers have been seeking for junctions linking all the known caves in a whole unique system, but the structural model may suggest prospective human-penetrable connections among different caves of the system might be actually not very probable from a geological point of view. If ever existing, they are due to a casual connection caused by local factors.

On the contrary, from a hydrological point of view, all karst systems of the Valle del Nosê belong to an unique drainage system, which has its output point where the syncline axis is at its narrowest, where an intersection with the present base-level occurs. The actually known parts of the system fit this model, but from their distribution we may deduce they are just a small portion of a much longer system, at the moment not yet discovered.

5. Conclusions

The detailed structural analysis allowed to define the relations linking the geometric arrangement of the endokarst system with bedding and jointing. The analysis particularly points out the development of endokarst galleries mainly follows the intersection of bedding with one of the two main jointing sets (longitudinal and transverse with respect to the main structure), causing the formation of galleries with different dip, different cross section morphologies and different hydrological function.

The most interesting result is in our opinion the pointing out of a relation of the geometric and 3-dimensional arrangement of the endokarst system with the main fold structure, and particularly with the presence of a multilayer geometry, with several neutral surfaces at different levels, which act as a barrier to karstification, so that the multilayer structure of the fold causes a multilayer structure of the karst system. This karst-fold relation may explain the main geometrical characteristics of the karst systems and allows to make anticipatory considerations on the arrangement and extent of eventually not yet explored karst systems connected to the main one.

The collection of structural data is therefore very important to the comprehension of deep karst systems, particularly where bedding and jointing are able to condition the underground water circulation.

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