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KARST MORPHOGENESIS AND TECTONICS IN SOUTH-EASTERN MURGE (APULIA, ITALY)

ABSTRACT: IURILLI V., CACCIAPAGLIA G., SELLERI G., PALMENTOLA G. & MASTRONUZZI G., *Karst morphogenesis and tectonics in South-Eastern Murge (Apulia, Italy)*. (IT ISSN 0391-9838, 2009).

The south-eastern border of the Murge plateau (Italy) is limited by the so-called «Soglia Messapica», which structurally separates the southernmost part of Apulia, the Salento peninsula, from the rest of the Apulian foreland. Here, the Murge plateau is characterized by a well defined karst landscape; in particular, the caves and their fillings represent potential geomorphological archives in which proof of recent tectonics may be found. Among the five caves considered in this study, the Grotta di Nove Casedde is the most representative; its forms have been analyzed in relation to the surface features. Hypogeous and surface data together have allowed us to individuate two tectonic phases recorded by fractures and breakdowns in speleothems. Analyses of the speleothems indicate that tectonic phases could have taken place before and after a phase of chemical deposition which is characterized by the growth of speleothems, aged 90 ka by means of Th/U analyses.

KEY WORDS: Neotectonics, Speleogenesis, Karst Morphosequences, Murge, Apulia (Italy).

RIASSUNTO: IURILLI V., CACCIAPAGLIA G., SELLERI G., PALMENTOLA G. & MASTRONUZZI G., *Morfogenesi carsica e tettonica nelle Murge Sudorientali (Puglia, Italia)*. (IT ISSN 0391-9838, 2009).

Il margine sudorientale delle Murge (in Puglia, Italia) è indicato nella letteratura classica come «Soglia Messapica»; esso corrisponde alla zona di separazione strutturale tra la Penisola salentina e il blocco dell'avampaese apulo. Le numerose cavità carsiche ivi presenti costituiscono, con i relativi depositi, possibili archivi geomorfologici dell'attività tettonica recente.

Tra la cinque grotte studiate, quella di Nove Casedde è la più rappresentativa; in questo lavoro se ne analizzano le forme in relazione a quelle di superficie. I risultati mostrano concordanza tra dati ipogei ed epigei nell'indicare la ripresa dell'attività tettonica in almeno due fasi, evidenziate da fenomeni di fratturazione e crollo in speleotemi; analisi Th/U collocano le due fasi a cavallo della formazione di speleotemi di 90 ka di età.

TERMINI CHIAVE: Neotettonica, Speleogenesi, Morfosequenze carsiche, Murge, Puglia

INTRODUCTION

In karst systems, hypogeous and surface landforms are linked despite their different vertical locations. As the hypogeous environment is relatively preserved by exogenous agents, its landforms may persist for a long time particularly in periods of low or no hydraulic activity. At the present time, most of the Apulian karst systems in the vadose zone are characterized by such conditions that may be considered at «low morphogenetic potential». Tectonics predisposes the speleogenesis, playing an important role also in the development of underground drainage networks and, thus, in the circulation of water (Knez, 1998). Its role in karst systems should be considered from two points of view: (i) as an energy input, both mechanic and potential, and (ii) as a morphogenetic agent, in case the karstic forms record the direct or indirect effects of shocks. The geomorphological data recognizable in caves have been useful in the reconstruction of recent tectonic behaviour, and of the series of seismic events occurred in both prehistoric and historic times (Forti & Postpischl, 1984; Postpischl & *alii*, 1991; Gilli, 1999; Gilli & *alii*, 1999; Lemeille & *alii*, 1999; Mocchiutti & D'Andrea, 2002). Therefore, also endokarst landforms must be studied arranging them in a network that represents a succession of morphogenetic events both depositional and erosive; this can be defined as the *morphosequence* (*sensu* Dramis & Bisci, 1998).

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This study has been carried out in the south-easternmost part of the Murge plateau (fig. 1). In particular, it concerns the caves located along the south-eastern area (fig. 2) close to the so-called Soglia Messapica, which approximately corresponds to the Taranto-Brindisi structural line. As a case study, the largest and best known cave was considered: the Grotta di Nove Casedde (*Pu 394* in the regional register of caves), located between Martina Franca (Taranto) and Villa Castelli (Brindisi). It was chosen due to the presence of numerous and well identified sets of fractures, also readable in the speleothems. The present paper has two purposes: (i) to establish the genesis of the surveyed forms, and (ii) to reconstruct the sequence of morphogenetic events, particularly those related to tectonic and/or seismic activity.

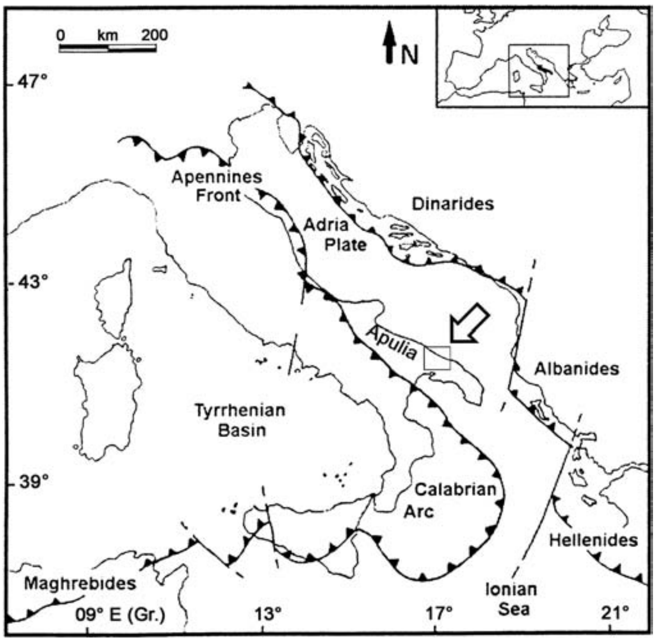

FIG. 1 - Geographic location and geodynamic setting of Apulia. The hatched and continuous lines indicate main faults; the lines with arrows indicate the front of the alloctonous. The box indicates the area reported in fig. 2.

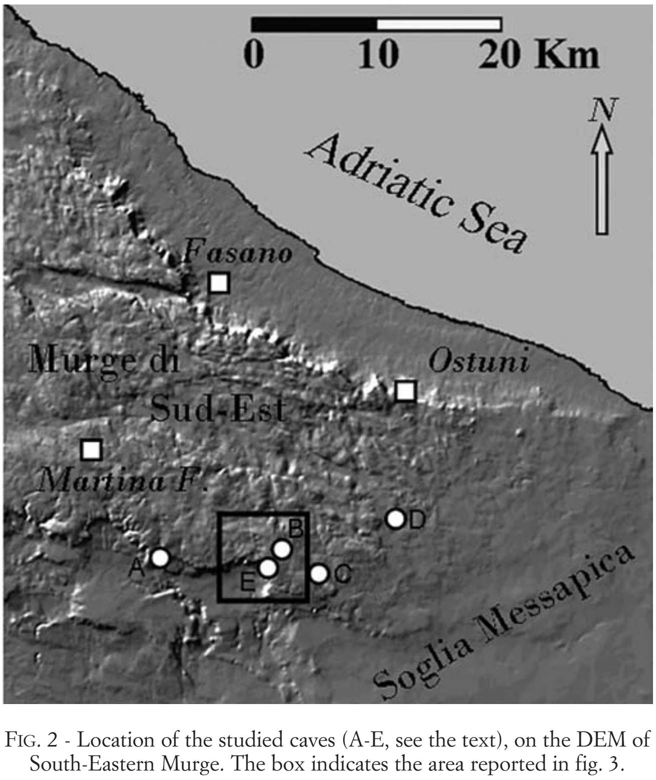

FIG. 2 - Location of the studied caves (A-E, see the text), on the DEM of South-Eastern Murge. The box indicates the area reported in fig. 3.

GEOLOGY AND GEOMORPHOLOGY OF THE SOUTH-EASTERN MURGE

The Murge Plateau is constituted by the Calcari delle Murge group, Mesozoic in age; its units have a monoclinal layering gently dipping SW with minor local deformations (Martinis & Robba, 1971; Ricchetti, 1975). It consists of various lithofacies: micritic and sparitic limestones, in part detritic, with variable porosity, and dolostones, or calcarenites with rudists. Such lithologic and textural variety predisposes the rocks to different kinds of karstification; the effectiveness of the process depends on the secondary permeability, which is due to the local stratigraphy and to the presence of tectonic discontinuities. With regard to these discontinuities and considering the age of the Mesozoic units, we must take into account that they include all the tectonic structures inherited since their diagenesis (Luperto Sinni & Borgomano, 1989).

The altitude of the south-eastern corner of the Murge plateau ranges between 220 to 520 meters a.s.l. On both the Ionian and the Adriatic sides it is bounded by slopes whose origin is yet matter of debate: according to some Authors, they are tectonic (Neboit, 1975; Baldassarre & *alii*, 1978); other Authors have recently considered the eastern slope, recognizable from Salento to Gargano, as the original edge of the Mesozoic carbonate platform (Bosellini & *alii*, 1999). Besides, according to Tozzi (1993), the slopes on the Ionian side correspond to the structures that uplift the Murge block with respect to Salento. Between Martina Franca and Villa Castelli the border of the Murge relief (fig. 3) is well represented by straight scarps elonged NS and WNW-ESE. The Murge monocline gradually slopes down towards Salento without well defined steps, being covered by Cenozoic marine deposits south of the Soglia Messapica line. The tectonics that produced the slopes is basically deemed Pliocenic, but it was followed by minor reactivations during the uplift of the area starting from the Middle-Pleistocene (e.g.: Baldassarre & *alii*, 1978; Iannone & Pieri, 1980; Doglioni & *alii*, 1994; 1996). Combined with eustasy, it also defined the terraces landscape, nowadays partly covered by a sequence of Late Pleistocenic deposits (i.e.: Hearthy & Dai Pra, 1992; Belluomini & *alii*, 2002).

As a result of the deep shaping of the Apulian platform, probably favoured by the endoreic drainage, the upper surface of the plateau shows only gentle undulations,

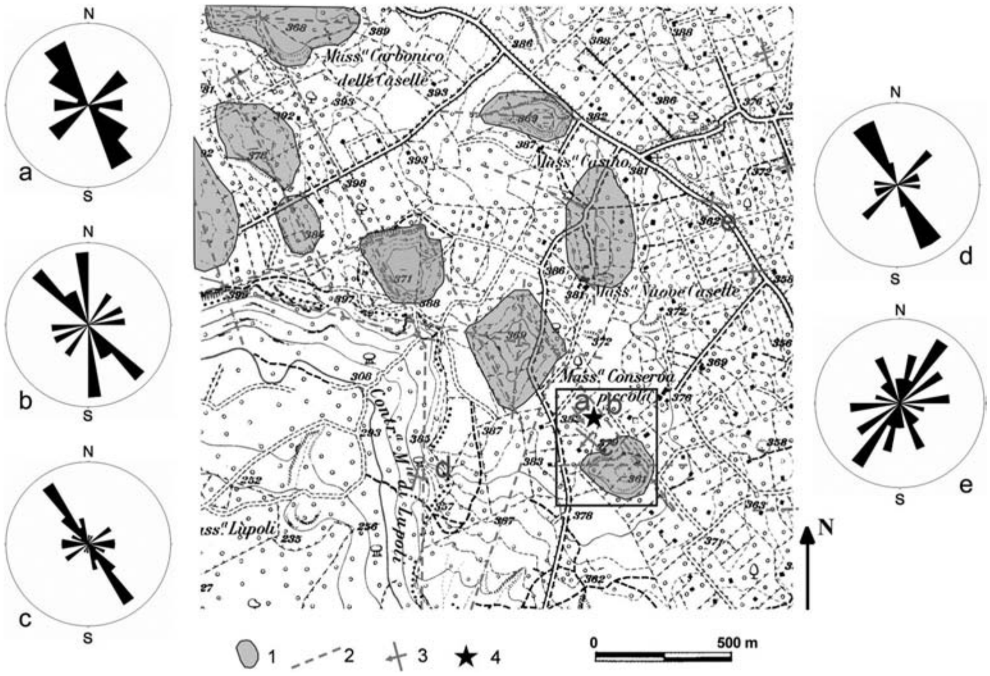

FIG. 3 - Morphologic features around Nove Casedde cave. As indicated in the text, the main structural-morphological alignments surveyed by aerial photographs correspond to erosive scarps and main axes of dolines, and fit to mesoscale structural data. *Legend*: 1) Main dolines; 2) Main alignments; 3) Strike and dip of bedding; 4) Entrance of the cave. *Base topographic map: IGM 1:25000 F° 202 I NE*. The surface survey sites are a,b,c,d,e, corresponding to the rose diagrams of the joint directions: a) over Nove Casedde cave (26 planes), b) East of the cave (19 planes), c) in the nerby doline (32 planes), d) on the slope West of the cave (29 planes), e) near *Specchia Tarantina* village (34 planes). The box indicates the area reported in fig. 4.

and cuts the continuity of the main tectonic structures. On that surface, the karstic landforms developed according to the structural conditionings, and define an articulated landscape with fluvio-karst forms and tectonically controlled polje-like karst depressions. The former are represented by two types of dry valleys: (i) small endoreic basins, developed according to the presence of tectonic depressions; (ii) some short and steep channels cutting the slope, which drain areas along the edge of the plateau; among the latter, the most important depressions having directions along the WNW-ESE axis (Valle d'Itria, Canale di Pirro); (Neboit, 1975). The whole surface is marked by numerous dolines, in some cases articulate; in many cases their distribution produces coalescent forms and isolated reliefs having the characteristics of an *inselberg* (Sansò & Triggiani, 2001). For the most part, the dolines show smooth forms and thick fillings with residual soils and *colluvium*, in some places alternating with ash deposits.

The rectangular drainage network, the aligned dolines and the anisotropic features in some of them lead to the individuation of a strong structural imprint in the landscape morphogenesis. The main axes of the drainage network are aligned ENE-WSW. The deepest valleys also show steep rocky slopes, often aligned with other elements of the landscape (fig. 3), like erosive scarps or main axes of adjacent dolines; in the same way some dolines have two axes of elongation, showing an articulated perimeter.

METHODS

The research was carried out through epigeous and hypogeous surveys following a sequence of operations that led to the study of the morphosequence (*sensu* Dramis & Bisci, 1998). Stereoscopic pictures and satellite images were investigated leading to the recognition of some morphological features related to tectonic activity on the karstic system. This called for a better field study which was performed mainly through surveys of epigeous and hypogeous landforms, whereby connections between them could be established (Iurilli, 2007). Surveys inside the cave focused on some «sites» where the deposits sequences appeared alternated with the found joints and/or displacements and their effects: 1 - fractures in the Mesozoic limestone; 2 - fractures in speleothems; 3 - recent detachement and collapse of blocks along joints; 4 - asymmetry in the growth of speleothems; 5 - fractures (even with displacement) in second generation concretions; 6 - joints, a few centimetres wide, between the local basement and the flowstone on the cave floor; 7 - fractures inside the same flowstone; 8 - fragments and/or chips of speleothems welded to the floor. After having surveyed the morphosequence of each site, the interpretation started by considering the local context: ì - the geometry of the site, of the speleothems and of the landforms produced by tectonics; ìì - the relation between different deposits, both chemical and clastic, and between deposits and joints and/or displacements.

THE STUDIED AREA

1 - SURFACE FEATURES

The studied area corresponds to the south-easternmost part of the Murge, marked by the relief of Mt. Trazzonara (m 425 a.s.l.). Except for the nearby slope of the plateau, the main elements of the local landscape are the flat surface, that shows the same features of the entire Murge, and the numerous dolines. Moreover, this surface is broken by steps lower than 1.5 m high, and by short channels, not more than some hundred meters long, converging into one of the dolines (fig. 4), close to the Grotta di Nove Casedde entrance.

The shape of the doline is noteworthy: its plan has two axes, oriented E-W and NW-SE; its profile shows two terraces, located at 350 m and 360 m a.s.l. (fig. 4). Lastly, the border of the depression looks «doubled» into an external and an internal one. In the surrounding area, joints have been identified in the local basement at a different metric scale (fig. 5). Among the sets of joints surveyed on the external surfaces, the one directed NNW-SSE is the most frequent, separated and karstified, while the others are less evident. Moreover the main joint directions correspond with the morphological features, e.g.

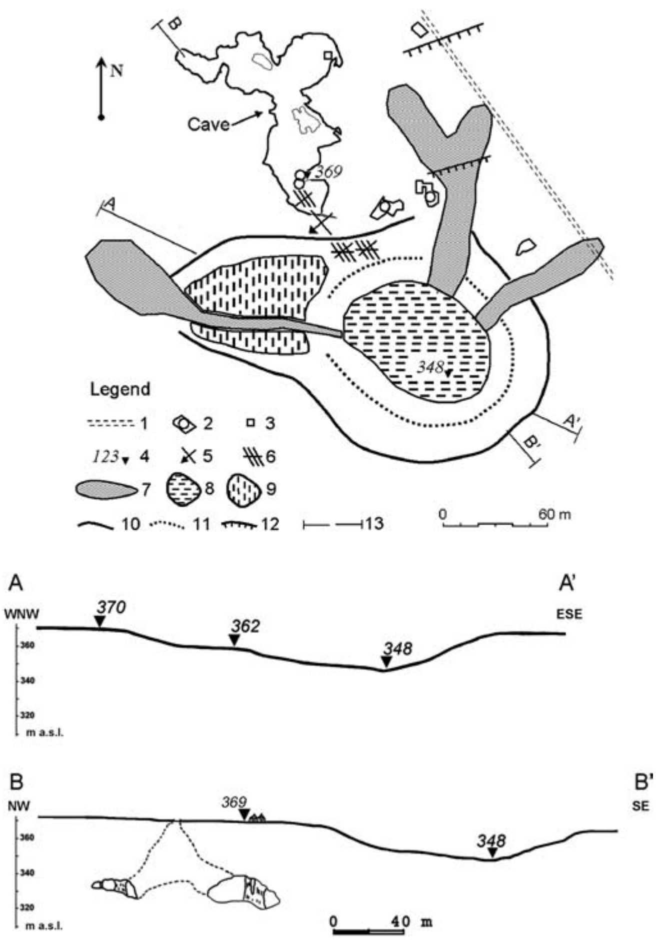

FIG. 4 - Nove Casedde (Martina Franca). *Above*: hypogeous and epigeous geomorphologic features, showing the projection of the cave on the surface; *Below*, sections through the cave and the doline (Iurilli, 2007 mod.). *Legend*: 1) country road; 2) buildings; 3) entrance of the cave; 4) elevation (m a.s.l.); 5) strike and dip of bedding; 6) main fissured epigeous zones (showing directions and density); 7) incisions; 8) doline bottom at 350 m a.s.l.; 9) doline bottom at 360 m a.s.l.; 10) external doline border; 11) inner doline border; 12) scarps (about 1.5 m); 13) sections.

FIG. 5 - a) Open and karstified fractures (strike about N 140°) outcropping on the surface straightly in correspondence to the Southern branch of Nove Casedde cave. Their dip is consistent with the fractures described in the cave (see text). The building in the background is also evident in fig. 4, represented with symbol 2. b) The same set of fractures can be seen on the ceiling of the southern branch of the cave, near the *Organo*; it outlines the eastern cave wall.

the short channels and the doline axes. The E-W set is also noticeable, in the direction of slopes and channels, as much as in the major axis of some doline, like the one considered here (fig. 4).

2 - The caves

In the studied area about 200 caves in about 700 km^2 are known (Giuliani, 2000). Five were chosen (fig. 2) to be surveyed in search of the above mentioned features; they are in a strip of land over the edge of the plateau, between Orimini, Mt. Trazzonara (to the west) and the hill of Montevicoli (to the east, near Ceglie Messapico). They are: A) the Grotta della Statale (Pu 537 in the register of caves of Apulia); B) the Grotta di Masseria Casino (Pu 1042); C) the Grotta del Cuoco (Pu 502); D) the Grotta di Monte Vicoli (Pu 522); and E) the Grotta di Nove Casedde (Pu 394).

The first one, Grotta della Statale (Pu 537), about 15 metres long, is conditioned by structures directed N 120° and dipping SW. Extensive chemical deposits, partly weathered, overlay a thick endoclastic deposit that narrows the volume of the void. Few joints cut the speleothems, with hardly any displacements.

The second cave, Grotta di Masseria Casino (Pu 1042), is a former hypogean, opened by slope erosion; it looks like a shelter about 70 square meters wide, presently used for agricultural purposes. Among its speleothems some complex columns still exist, in which the only interesting feature is the fracture cutting them with a slight displacement.

In the complexity, Grotta del Cuoco (Pu 502) (Palmisano, 1981) is second in size compared to the Grotta di Nove Casedde. The morphosequences recognised here include both chemical and graviclastic deposits, tilted speleothems, joints and displacements corresponding with tectonic structures.

The Grotta di Monte Vicoli (Pu 522), although relatively small, is rich in deposits and speleothems. Having been used as a show cave for decades, it has suffered damages, but many fractures and collapse phenomena are due to natural processes, since they have been fossilized by the growth of subsequent speleothems.

2a - The Grotta di Nove Casedde

The possibility for describing and interpreting deposits and fractures more widely than just in the nearby caves, makes Grotta di Nove Casedde the most representative in this study. The cave has three main axes, corresponding with its main branches (fig. 6a): the entrance cavern, the western branch and the southern branch. The entrance is a collapsed ceiling in a huge domed cavern, about 20 meters high, whose floor is covered by a talus cone (fig. 6b). At the foot of the talus, a terrace («T» in figure 6b) formed by limestone blocks partly fossilized by a flowstone leads to the southern and western branches of the system. Among the depositional landforms, such flowstone is the most frequent across the cave floor.

Western branch

The floor is composed of a deposit of large blocks, partially cemented between them by a discontinuous flowstone, on which short stalagmites of about 0.1 m high rise. This flowstone has a yellowish colour and is unweathered. The cave floor goes down a few metres in narrow spaces between the clastic cemented deposit and the limestone wall. It is almost covered by the older flowstone fossilizing a deposit of some meters thick. Some interstices among the largest blocks are accessible; in the voids stalagmite and stalactite fragments, fallen from the ceiling can be observed. They indicate a complex and ancient history with different phases of cave enlargement, speleothems collapses, weathering and chemical deposition. In this branch of the cave a huge fragment of speleothem is recognisable; it is 2.75 m long and lays upside down, tilted at the foot of a similar speleothem, which is still standing and is thought to be the original base of the fallen portion (site VI). The space over the truncated speleothem base is about 1 m high, not enough to contain the fallen portion (fig. 7a). In the adjacent room (site VII) a column (fig. 7b) having a mean diameter of about 0.5 m is divided by vertical joints into blocks that are still in place. Fig. 8 outlines the geometric relations between the surveyed deposits. The ceiling of site VI is represented by an oblique wall oriented N 120°, which is also the southern border of the northern and western branches of this cave.

Southern branch

The deepest and largest cavity, about 50 m long and 50 m wide, is oriented along the N-S axis. Its decorations are mainly grouped in imposing stalagmitic and columnar sets, two of which are named *Tempio* (the Temple) and *Organo* (the Pipe-Organ) (Orofino, 1970); this latter reaches 20 m in height, where it connects the ceiling with the deepest bottom. The ground deposits are blocks and slabs fallen from the above mentioned limestone wall, and they have rolled along the talus cone below the entrance of this branch. Most of the ground deposit is fossilized by calcite in the form of flowstone and by small simple stalagmites, up to 2.5 m high. The survey of the interstices in the deposit allowed us to estimate its thickness to be a minimum of 5 m. The flowstone found here shows the same features of the one observed in the western branch.

The walls of this chamber are made of hanging limestone layers, and its ceiling is the outer face of a less fractured layer (fig. 5b), where the visible joints are directed about N 60°, N 130°, and N 180°. The *Tempio* is the other complex of speleothems connecting the cave floor to the ceiling. Its dimensions are around 10 m in each direction, and it shows many generations of concretions, represented by stalactites, stalagmites, columns and flowstone. On its southern side, the ground deposit is made up of huge blocks larger than 1 m, in part fallen from the same group (fig. 7d).

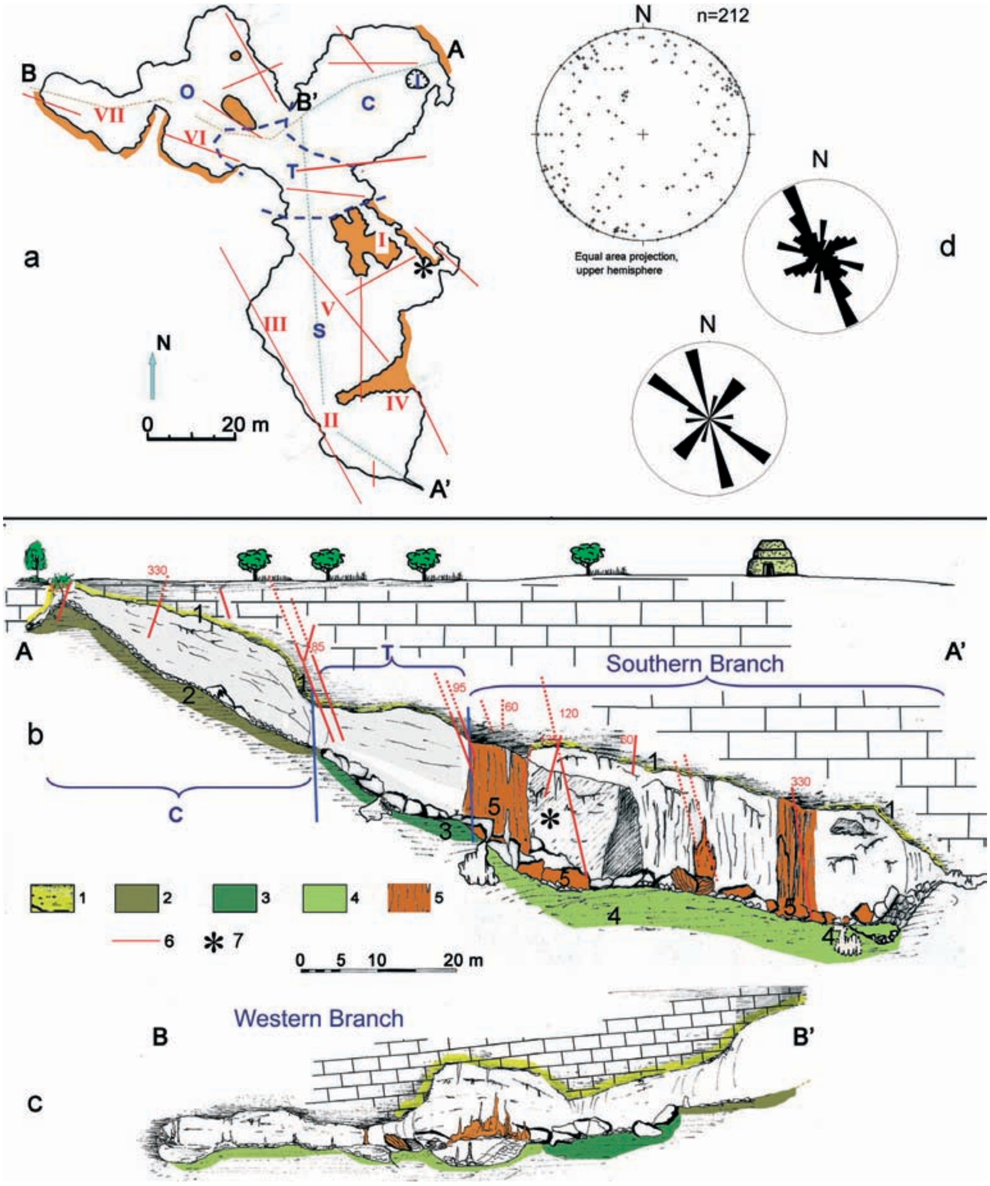

FIG. 6 - Nove Casedde cave: a) Zones, sites (I to VII) and main sets of joints on the plan of the cave; b) section A-A' (NS), showing the setting of deposits and the main fractures; c) section B-B' (WE); d) poles of the planes (above) and rose diagram (in the middle) from the structural survey in the cave; rose diagram of the cave elongations (below). *Legend*: I) Entrance, C) Dome chamber; T) Terrace, O) Western branch, S) Southern branch (see also section A-A'); I to VIII: the sites analyzed in detail; 1) Exposed limestone; 2) Talus cone; 3) Accumulation of ceiling blocks; 4) Endoclastic deposit, heterogeneous, cemented, with fragments of large speleothems; 5) Main speleothems of the oldest series; 6) Main tectonic joints; 7) Place of stalagmite sampling.

2B - JOINTS DESCRIPTION

Among the four main sets of joints characterizing the whole cave (fig. 6), the NW-SE direction, dipping both NE and SW, prevails. The joints belong to sets corresponding to the main morphological features of the cave. Some of them widely affect the whole columnar formation of the speleothems named *Tempio*. Those oriented between N 110° and N 120° break the continuity between the eastern wall of the cave and the *Tempio* (site I in fig. 6a). In this speleothem joints are oblique and generally open up to 20 cm; they show forms of past fractures with rough surfaces and many of them are filled with calcite, broken by more recent fractures. The set with strike between N 140° and N 150° is also present on the surface; at a larger scale, it is also recognizable as alignments in the landscape as described before. In some places they cut the one directed N 110°÷120°, thus showing their younger age. Less readable joints affect minor speleothems, representing at least two phases of concretion/fracture (sites II and III).

Analogous to the *Tempio* is the *Organo*, a huge group of speleothems located in site IV. Dissimilar to the *Tempio*, a set of joints with strike between N 130° and N 150°, dipping NE or nearly vertical, is prevalent here. Apart from these, an open joint, without secondary concretions, crosses the whole group determining an approximately 50° inclined surface toward its eastern end (fig. 7e). The limestone wall south-east of the *Organo* stands from floor to ceiling and is marked by a set of dense and parallel fractures (fig. 5b); it has only a few speleothems, small stalactites and some short columns. One of these has grown by climbing, while a larger one is crossed by the same joint that crosses the *Organo* (fig. 7c).

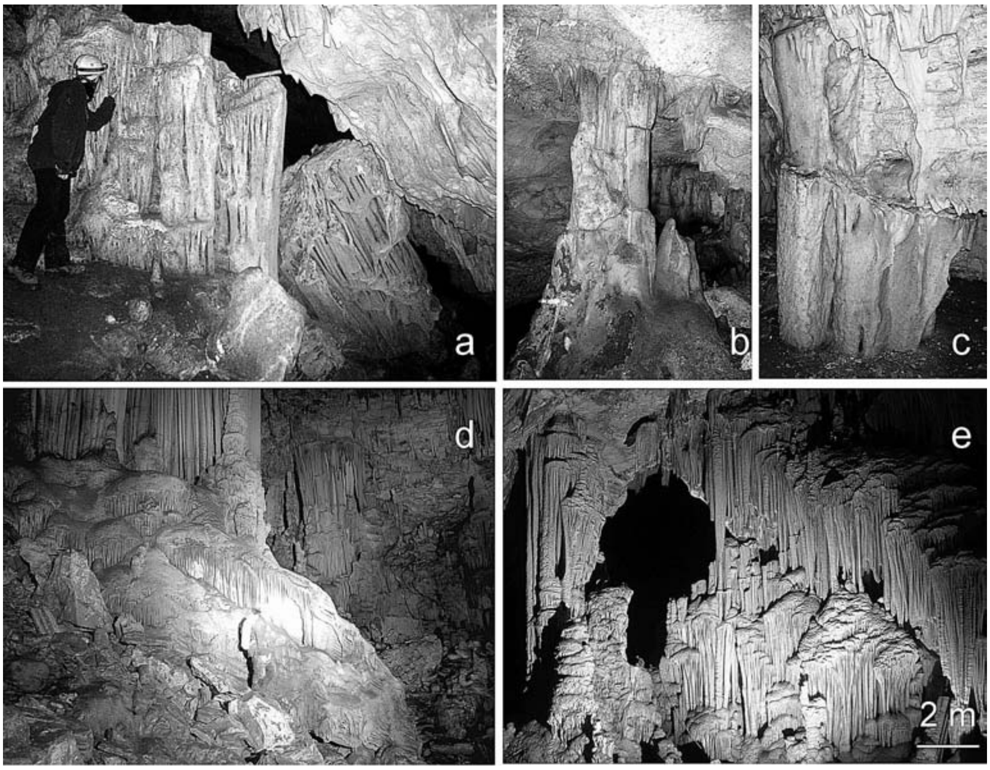

FIG. 7 - Speleothems in Nove Casedde cave. a) The upside-down speleothem (right) in site VI; b) Fractured column (site VII); c) Fractured column (site IV); d) Huge block at the foot of the «Temple», fossilized by speleothems; e) The *Organo* with its main oblique fracture.

North-west of that, a former stump of speleothem laying on the floor, across the main axis of the chamber, is welded to the deposit by secondary calcite and fossilized by the flowstone diffused across the entire floor (site V). An open fracture breaks it in the middle, cutting also the overlying flowstone; the western end of the joint is also lowered about 3 cm.

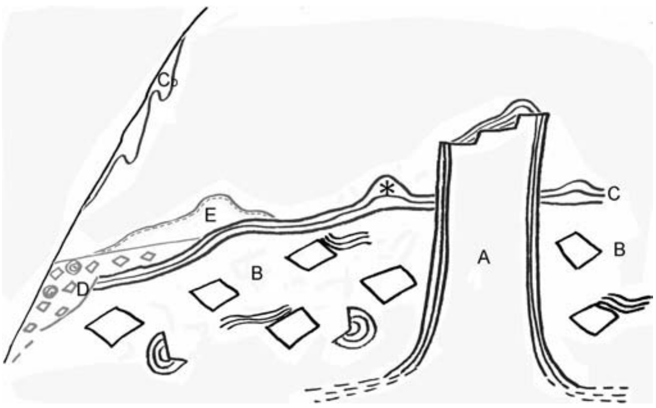

FIG. 8 - Sketch of the relations among the karst fillings in Nove Casedde cave (out of scale), referring to site VI. Legend: A) The oldest series of large speleothems, locally fractured and weathered. B) Breakdown deposit (limestone blocks and slabs and fragments of speleothems) with local calcite deposit. C) Flowstone cover with short stalagmites, and wall and ceiling speleothems (C_b). D) Clastic deposit (calcite fragments and chips) in fractures. E) Recent and active white calcite concretions. *) Stalagmite samples (see table 1 and fig. 9).

3 - GEOCHRONOLOGICAL ANALYSES

Recent speleothems, quite fresh and still active, are characterized by a creamy yellow colour. They are diffused all along the perimeter of the cave and on the ceiling. It is possible to recognize the same depositional facies in the different sites, particularly in a deposit with stalagmite growth on an important fracture surveyed in site I. Three samples (figg. 8, 9) have been dated by Cerak (Mons, Belgium) using the $^{230}Th/^{234}U$ method, aiming to obtain some chronological constraints for the reconstructed sequence of the process that shaped the «morphosequence type». Samples no more than 0.1 m long have been obtained from sampling entire stalagmites. They were cut in laboratory in order to isolate the bottom levels; in any case only their cores have been analyzed, ruling out weathered parts.

The obtained radiometric ages are reported in table 1. The isotope ratios were analyzed by a-spectrometry. The activities were calibrated by adding known quantities of radioactive spikes (^{232}U-^{238}Th). This chemical preparation was based on the method proposed by Bernat (1969) and Gascoyne (1977) modified by CERAK. With regards to the method of analysis, two conditions cannot be disregarded: 1) the ratio $^{230}Th/^{234}U$ must be = 0 at the deposition time; such a condition can be modified by the presence of clay, iron oxide or hydroxides, although the erosion of old limestone may also have polluted the speleothems. In general, the presence of a pollutant is indicated by the $^{230}Th/^{232}Th$ ratio. The analysis is considered reliable when this ratio is >20.

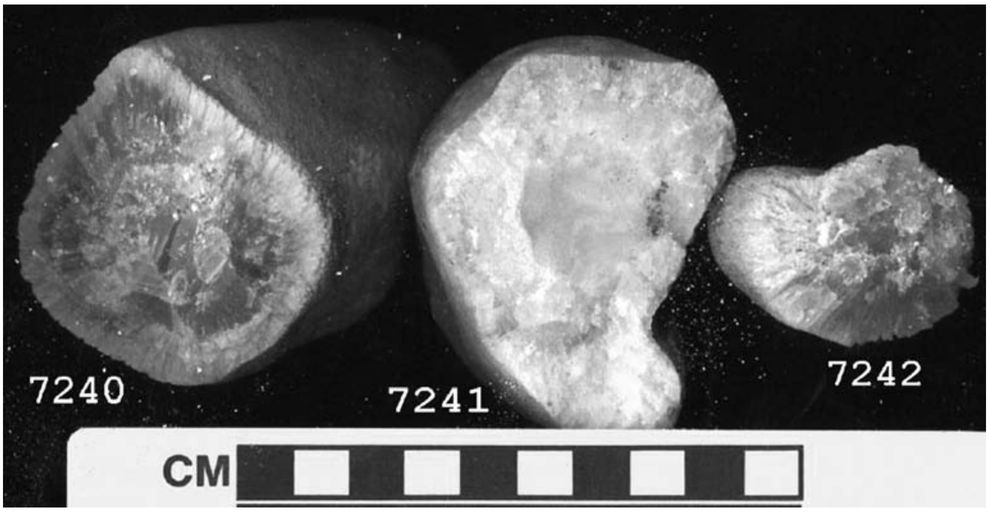

FIG. 9 - Stalagmite samples used in the geochronological analyses.

TABLE 1 - Results of the radiometric analyses on three samples of stalagmites (Cerak laboratory, Mons - Belgium).
Analyses were performed at Cerak (Centre d'Etude et de Recherché Appliquées au Karst) of Mons University (Belgium) using alpha spectrometry. Column ***a***: total concentration of U [ppm] occurring in the sample. Column ***b***: the $^{234}U/^{238}U$ activity ratio which is distinctively marked by values different from 1 in underground waters and in speleothems. Column ***c***: the $^{230}Th/^{234}U$ activity ratio which is the real chronometer. Column ***d***: the $^{230}Th/^{232}Th$ activity ratio gives an indication of the «contamination» of the speleothem since the occurrence of ^{232}Th in a speleothem indicates that the ^{230}Th could be received from a different source than ^{234}U. A reliable age is indicated by a $^{230}Th/^{232}Th$ activity ratio higher than 20; lower values could indicate an older age due to the presence of foreign ^{230}Th coming from sediment contaminants. Column ***e***: the $^{234}U/^{238}U$ activity ratio indicates the initial geochemical ratio of the analysed sample; present sea-water is marked by values of this ration of about 1.14. Column ***f***: the age of the analysed sample along with the time range reliable at 67%

Camp.	a [U]ppm	b $^{234}U/^{238}U$	c $^{230}Th/^{234}U$	d $^{230}Th/^{232}Th$	e $[^{234}U/^{238}U]t=0$	f Età (ka)
7240	0,278±0,002	1,012±0,007	0,561±0,010	92±17	1,015	89,2[+2,6/–2,6]
7241	0,125±0,001	1,014±0,010	0,954±0,049	—	1,036	> 250
7242	0,083±0,001	1,015±0,020	0,519±0,135	3,7±1,8	1,018	79,3[+36/–27]

2) The speleothems must be chemically closed during their life-time. In particular, for the above reason, only the inner part of the cleanest speleothems not affected by chemical corrosion, have been analysed.

The results confirm the difficulties of this kind of analysis in karstic geochemical systems; the value 89,2 ka (± 2,6), relative to sample 7240 is the most probable since it shows the best $^{230}Th/^{232}Th$ ratio (as it is >20), and thus the character of a closed system with respect to external ^{230}Th.

DISCUSSION

The described data have allowed us to individuate different events of deposition (both chemical and clastic), weathering, and tectonics, but mainly to put them into a relative time scale, identifying a «morphosequence». The morphological survey carried out in the surroundings of the Grotta di Nove Casedde has shown that discontinuities belong to well-defined sets of directions. Thus the fractures must be due to tensile tectonic stress more than to a generic tension release; the hypothesis of their relation with decompression derived from subaerial erosion of the upper part of the carbonate sequence (i.e.: Sjöberg, 1994) can be excluded, mainly because of the depth on which the joints were surveyed, and for the relative low erosional rate of the surface. Further, the diagrams of the joints and of the main cave elongations are similar (fig. 6d), suggesting a primary role of tectonics in the origin of the cave contour surfaces. The spreading of the joints on the speleothems indicates their activity after the recent phases of concretions.

As shown in previous works (e.g. Crispim, 1999; Forti, 1999; Riva, 1999), fractures in speleothems may also be due to events other than tectonics. In the proposed study case there are not elements supporting alternative hypotheses: 1) fractures as an effect of impact need the evidence of fallen blocks of adequate size and weight, such is not found here in the case of large fractured speleothems nor in the case of the flowstone; 2) fractures as an effect of flooding need signs of embrication on the transported elements, or a granulometric selection of the clasts; 3) collapsing due to floor constipation or erosion imply centripetal or disorganised deformations. In the Grotta di Nove Casedde only very recent anthropogenic fractures have been recognised; these affect the smaller speleothems. In the absence of the above mentioned premises, the most possible interpretation of the hypogeous evidence would have to be tectonics.

The sequence in the western branch is fundamental in recognizing the alternation of periods of prevailing deposition or fracture. In site VI, the size and the forms of two blocks together indicate that the fractured speleothem had been a column connecting the floor to the ceiling. The supposed base of the fallen stump is still vertical (fig. 7a), without any signs of fracture, nor tilting; this excludes the collapse for ground subsidence. Even the breakdown by impact has to be excluded, because a block of adequate dimension is absent.

On the contrary, in the nearby site VII, the column is broken but still vertical (fig. 7b); this may be interpreted as a consequence of a small offset, enough to break the calcite, but still not enough to move the blocks. As the joints are almost vertical, they can be explained as the effect of compression on the column (Crispim, 1999).

The features observed in the southern branch have been related to a set of sub-vertical joints with strike between N 135° and N 150°. They are as open in the cave as they are in the epikarst; even if set in an active karst system, they are uneven and rough, without any subsequent concretions. It can be concluded that the recent opening is due to extensional forces. Since the fractures cut the flowstone on the floor, correlated with the speleothems crystallized about 90 ky ago, they should be connected to a more recent breaking phase.

Therefore epi-and hypogeous data support the idea of a recent tectonic re-activation of the speleogenetic structures in the Grotta di Nove Casedde. In this context, the wall between the southern and the northern branches of the cave, oriented N 120°, is thought to have had an activity during the recent evolution of the cave, with the following features: 1 - an offset larger than 1.5 m, because of the length of the fallen column; 2 - two secondary phases of direct displacements, the first (T1a) recorded in site VI (with the fallen column according to the evolution outlined in fig. 10), the second (T1b) in the fractured column in site VII; 3 - a possible left strike-slip component in the first secondary phase, as indicated by the breakdown stump direction. The above described displacements indicate a first (T1) extensional (or transtensional) tectonic phase, in which the secondary phases T1a and T1b may be distinguished.

The following events, that opened the NNW-ESE oriented fractures and shaped the walls of the Southern branch, may indicate a second extensional tectonic phase (T2).

In the same way, the contribution of surface morphology outlines at least two distinct phases of esokarstic dynamics:

– phase «A» - shaping of a flat doline with an evident W-E elongation (external doline), maybe a consequence of a tensile stress phase along the N-S axis (according to Vandycke & Quinif, 1999); the correlation with the above mentioned T1 phase is possible, since, from the geometric point of view, the extension on W-E oriented structures should not be in contrast with a transtension along N 120° oriented structures.
– phase «B» - further downward inside the doline, with a prevailing morpho-structural direction NNW-ESE, after a tensile stress phase about SW-NE oriented; the correlation with the T2 phase (see above) is possible.

Topographic surveys and joint analysis indicate that the fractures oriented between N 135° and N 150° are present both in the Nove Casedde cave and along the doline slope. These fractures seem connected to the speleogenesis of the southern branch; in the correspondent external areas they are dominant in size and number, with respect to the others. The localisation of the «inner doline» indicates that its origin could be related to the collapse of part of the Nove Casedde former cave system (fig. 4). Phase (B), as a consequence, must be more recent than 90 kys (fig. 11). This situation should be in accord with the recent geodynamic interpretation proposed by Di Bucci & *alii* (2009).

On the flat surface straightly above the cave we cannot distinguish forms due to the vertical displacements, except for some short steps (e.g. the ones in fig. 4) whose strike is different from N 120° (the structure active in T1). However, considering the rates of solutional lowering of limestone surfaces (Ford & Williams, 1989; Gabrovček, 2009), it is possible to assume that short fault steps, related to the displacement recorded in the cave, may have been con-

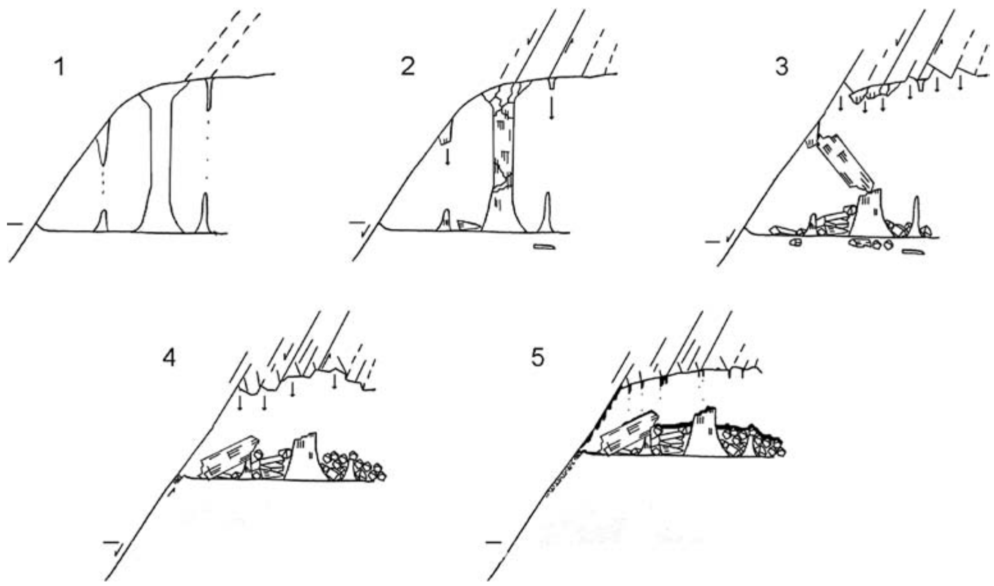

FIG. 10 - Evolutionary sketch (out of scale), deduced from the analysis of the karst morphosequences surveyed in Nove Casedde cave and, similarly, in other caves. In particular it explains the sequence of site VI (North-western branch of the cave) also reported in fig. 8, and its overturned speleothem. The horizontal dash on the left of the fault plane, is a reference level corresponding in (1) to the starting position of the cave floor.

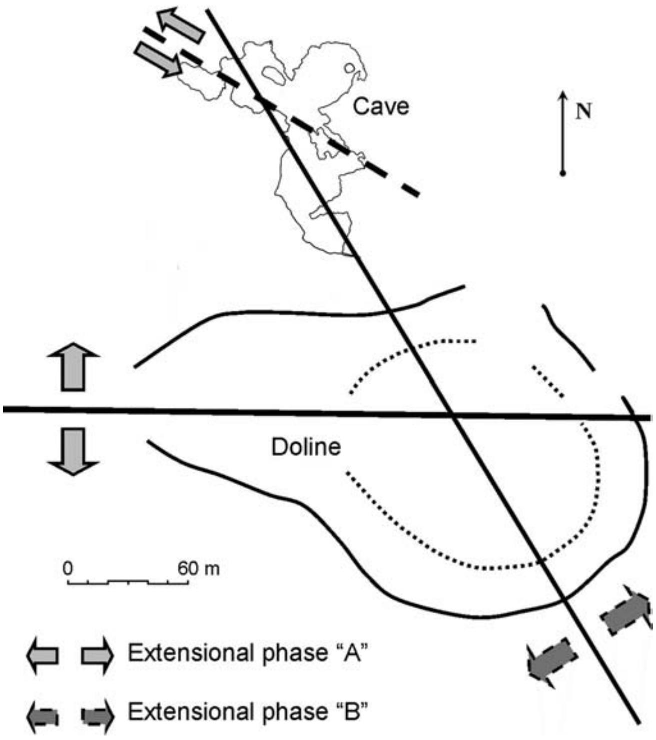

FIG. 11 - Displacement directions as inferred from the morphological study of the cave-doline karst system of Nove Casedde. A and B tectonic phases are described in the text. The extensional phase «A» is represented in the cave in the site VI (cfr. fig. 7a, b), where a left-lateral slip on a N 120° plane may be recognizable.

cealed on the surface landscape in the time ensuing their shaping.

CONCLUSIONS

The whole data set points out an evolution of the landforms, all along the Upper Pleistocene, in a cave that must certainly be older than the described forms, because it had already been well developed at the time when the studied morphosequences started to be shaped. However, a tectonic activity from more recent times has been revealed. Eso-and endokarst show parallel evolutions, mainly ruled by the (re)activation of extensional tectonics. The directions of the displacements, inferred by the analysis and interpretation of cave morphosequences and of landforms, are consistent with the scheme outlined in fig. 11. The geochronological data have led to the individuation of a phase of concretion comprised between two important morphodynamic phases, responsible for the cave and exogenous surface evolution. Before 90ka ago, an important succession of hypogeous breakdowns was the consequence of tectonic exstensional fractures (T1 phase) in the Mesozoic local sequence and in the huge speleothems of the *Organo* and the *Tempio*. After this, in a morphogenetic environment characterised by recent extensional fractures, a phase of chemical deposition followed, having been responsible for the sampled stalagmite growths and for the *flowstone* deposition in the surveyed caves but also in other caves of Apulia (Mastronuzzi & *alii*, 2007). This phase has been marked by the high rainfall and temperate climate which characterised the latter part of the last interglacial - may be the MIS 5.2 - in a context of weather deterioration in cold-dried direction typical of MIS 2 in Southern Italy (i.e.: Watts, 1985; Prentice et al., 1992; Rossignol-Strick et al. 1992; Rose & *alii*, 1999).

The opening of new fractures in the largest speleothemes, among them the *Tempio* and *Organo*, together with reactivation of pre-existent fractures, is due to a second tectonic phase (T2), possibly extensional and younger than 90 ka.

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