Il Quaternario
Italian Journal of Quaternary Sciences
11(1), 1998, 89-94

KARST GEOMORPHOLOGY OF THE VALLONE DI FURORE, SORRENTINE PENINSULA (ITALY)

M. Coli - L. Piccini
Dipartimento di Scienze della Terra, via G. La Pira 4, 50121 Firenze, Italy

ABSTRACT - The discovery of endokarst forms and in-fills, during the construction of a water-pipe tunnel in the rock wall of the Furore valley, has moved us to a new understanding of the geologic and geomorphologic setting in which karst developed. In the area, in fact, limestone outcrops display a long evolutionary history of karst, ranging in age from Jurassic up to Present, strongly controlled by lithology and neotectonics. Paleokarst occurred during the formation of the Jurassic carbonate platform, whereas a long stage of continental karst affected Jurassic limestone during a pre-Miocene phase of emersion. A neokarst stage begiame in the Pliocene, during the development of a low-gradient erosion surface, but during the Early Pleistocene block-faulting, the karst systems were disconnected and truncated by faults. A last stage of neokarst occurred in the Middle-Late Pleistocene, during the uplift of the whole area in respect to the sea level. The large cave discovered in the tunnel and the small phreatic caves, formed by the mixing of continental and sea waters, developed during this stage.

RIASSUNTO - Durante la costruzione di due gallerie artificiali per scopi idraulici, scavate nelle ripide pareti del Vallone di Furore, sono state intercettate diverse cavità carsiche, riempite e non, di dimensioni anche rilevanti e tali da creare problemi alla prosecuzione dei lavori. Lo studio geo-morfologico di tali fenomeni ha permesso una più dettagliata ricostruzione delle diverse fasi di carsificazione, che hanno interessato l'area di Furore a partire dal Giurassico sino al periodo attuale. Un primo evento paleocarsico si manifesta sotto forma di cavità riempite di brecce sinsedimentarie all'interno della piattaforma giurassica Brecce a matrice argillosa giallastra riempiono invece cavità paleocarsiche, probabilmente sviluppatesi durante il lungo periodo di emersione cui è andata soggetta la piattaforma carbonatica sorrentina sino all'inizio del Miocene, quando il sovrascorrimento di calcari cretacei sopra i calcari giurassici fossilizza anche queste morfologie carsiche. Il ciclo neocarsico ha inizio durante il Pliocene, in concomitanza con la fase di modellamento che porta alla formazione delle superfici a basso gradiente, di cui rimangono attualmente tracce lungo i crinali dei rilievi intorno ai 900-1000 m di quota. A questo periodo sono ascrivibili anche i depositi di terra rossa che riempiono alcune forme carsiche relitte sia superficiali che profonde. Il paesaggio pliocenico subisce un primo modellamento tettonico durante il Pleistocene Inferiore, con la formazione di ingenti accumuli detritici ai piedi dei rilievi e lo smantellamento di buona parte delle morfologie carsiche superficiali. Con questa prima fase tettonica l'area di Agerola si configura come un bacino chiuso in cui vengono convogliate, per via sia superficiale che sotterranea, le acque delle aree circostanti. In questa situazione idrogeologica si ha lo sviluppo di sistemi carsici di cui la Grotta di S. Barbara, che si apre attualmente alla sommità delle pareti che troncano la Piana di Agerola verso Sud, rappresenta probabilmente un frammento. La tettonica tardo pleistocenica, responsabile dello sprofondamento di rilievi posti a Sud di Agerola, tronca, disattivandoli, questi sistemi carsici e porta ad una rapida ristrutturazione dell'assetto idrogeologico. Il gioco di queste faglie porta in affioramento alcune di queste cavità, per lo più riempite da detriti di crollo, che oggi appaiono come caverne lungo i settori medio-alti dei versanti del vallone di Furore. Le ultime fasi neocarsiche agiscono durante il progressivo sollevamento dell'intera penisola sorrentina. Ad una nuova fase di sviluppo di morfologie carsiche superficiali, limitate per lo più a forme di dissoluzione a scala piccola, si accompagna la formazione di cavità sotterranee lungo i principali set di fratture. La grande cavità intercettata dalla galleria superiore è probabilmente una di queste cavità relativamente recenti. Nella galleria inferiore si trovano invece cavità prodottesi in seguito a fenomeni di miscelazione tra acque dolci di origine continentale e acque marine. Tali cavità sono ben correlabili con antichi solchi di battente che incidono le falesie a quote leggermente superiori. Ad una fase di basso eustatico, probabilmente legata alla glaciazione würmiana, si deve lo sviluppo di cavità al di sotto dell'attuale livello marino, che funzionano attualmente da sorgenti sottomarine.

Key-words: karst, speleogenesis, Sorrentine Peninsula
Parole chiave: carsismo, speleogenesi, Penisola Sorrentina

1. INTRODUCTION

The excavation of artificial tunnels and wells in limestone massifs often lead to the discovery of caves, and other endokarst phenomena, which are not detectable from the surface. These "lucky" events allow the study of active endokarst not directly accessible by man, and of paleokarst not yet exhumed by the surface morphogenetic agents.

In the Sorrentine Peninsula, which forms the southern arm of the Gulf of Napoli (Italy), the construction of a water-pipe tunnel allowed us to study some endokarst forms and in-fills. In particular, a large unsuspected cave, which represents one of the largest known caves in the area, was discovered at an elevation of 360 m a.s.l..

The importance of these discoveries is due to the fact that the whole Sorrentine Peninsula is a wide carbonate area where surface karst forms are rare because Late Pleistocene morphotectonic events cancelled most of the previous karst landforms.

2. GEOLOGICAL SETTING

In the geo-tectonic frame of the southern Apennines, the Sorrentine Peninsula is a horst (fig.1) consisting of a Jurassic carbonate platform, paraconformably topped by a thin layer of a clastic deposit of Late Miocene, of the Alburno-Cervati tectonic unit (Pescatore

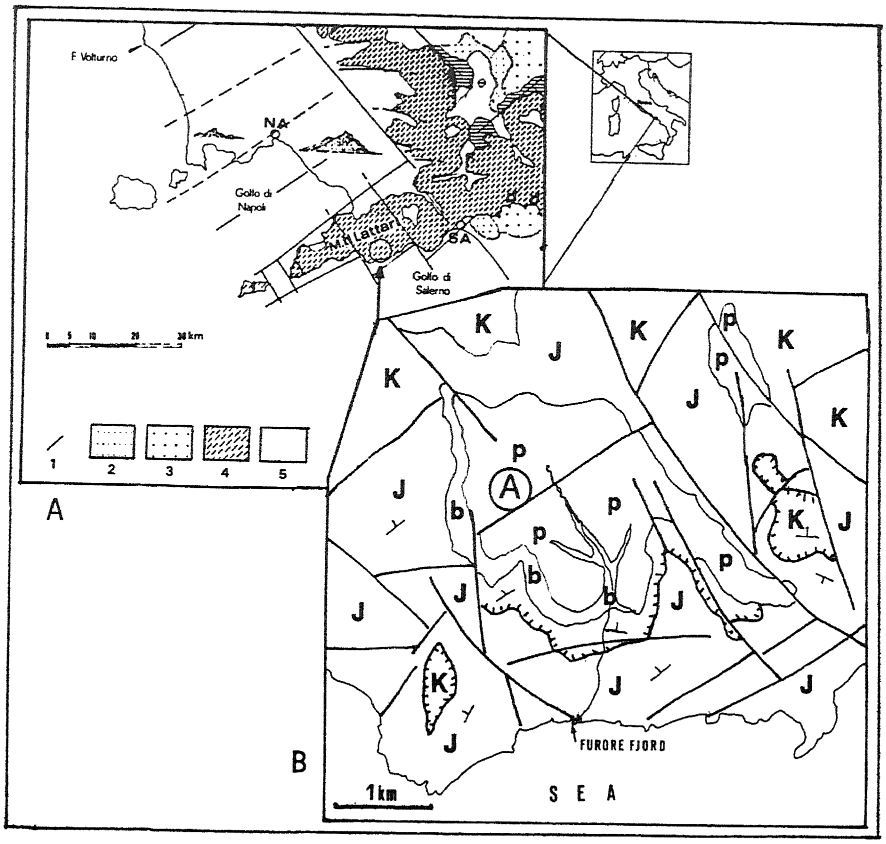

Figure 1. Synthetic geological sketch map of the of the Sorrentine Peninsula horst (A). Key: 1= main fault systems; 2= Ligurid Units; 3= Sicilid Units; 4= Internal Campane Units; 5= Plio-Pleistocene deposit; NA= Napoli; SA= Salerno (modified from Pescatore & Ortolani, 1973). Geology of the Furore area (inset B): p= piroclastic deposit; b= crio-clastic deposit; K= Cretaceous limestone; J= Jurassic limestone; A= Agerola town.

Schema geologico dell'area della penisola sorrentina (A). 1= principali sistemi di faglie; 2 = Liguridi; 3= Sicilidi; 4 = Unità Campane Interne; 5 = depositi Plio-Pleistocenici; NA = Napoli; SA = Salerno (modificata da Pescatore & Ortolani, 1973).

Geologia dell'area di Furore (B): p = depositi piroclastici; b = depositi crio-clastici; K = calcari cretacei; J = calcari giurassici; A = Agerola.

& Ortolani, 1973; Capotorti & Tozzi, 1991). This sequence is tectonically overlain by Late Createceous limestone of a carbonate platform. The overthrust took place in Late Miocene - Early Pliocene, during the main phase of the Southern Apennines orogenesis (Pescatore & Ortolani, 1973; Ortolani, 1978; Cinque, 1980).

In Early Pliocene, extension tectonics affected the whole area with low-angle faults (D'Argenio *et al.*, 1986). In Early Pleistocene the block-faulting, related to the opening of the Thyrrenian Basin, divided the tectonic edifice into a number of highs and lows (Brancaccio & Cinque, 1988). Capotorti & Tozzi (1991) pointed out that block-faulting rotation also played an important role in this tectonic phase, as well recorded by the several strike-slip faults visible along the Sorrentine Peninsula cliffs. After this tectonic phase a thick layer of cryo-clastic deposit draped the slopes during a stage of low tectonic activity (Brancaccio & Cinque, 1988; Aucelli et al., 1996). A regional uplift occurred in the Late Pleistocene. Successively the volcano-clastic deposit of the Somma-Vesuvio volcanic edifice covered the area (Sgrosso, 1971).

The tectonic setting of the Furore area is summarised in fig.2. The overthrust between Jurassic and Cretaceous limestone is about at 500 m a.s.l., gently dipping towards N.

Jurassic limestone is not tectonically disturbed, whereas Cretaceous limestone is strongly but cohesively cataclastic. Main fault systems bound the Agerola graben and form the steep fault scarp along the coast, fault planes dip about 60÷70° towards the plane. Jurassic limestone dips towards NNE of about 15°, Cretaceous limestone dips towards W of 30÷40°, the clino-stratification of the cryo-clastic deposit dips towards NW about 40÷50°.

Fracturing strongly affects Jurassic and Cretaceous limestone; fractures are both widespread and concentrated in bands ranging from a few metres up to fifty metres wide. The fracture bands are sub-vertical and grouped into three systems: the main one trends SW-NE, the others NNEN-SSWS and NW-SE (fig.3).

3. GEOMORPHOLOGY

The Sorrentine Peninsula branches into the Thyrrenian Sea with a NE-SW direction (fig.1), and it is about 20 km long and 4 to 8 km wide. Its present geomorphic setting has been developing for the last 2 Ma (Aprile *et al.*, 1978), mainly during the Early Pleistocene, when the whole area experienced an intensive block-faulting.

The morphotectonic setting of the Agerola-Furore area is mainly due to the Early Pleistocene neotectonics that dissected a low-gradient

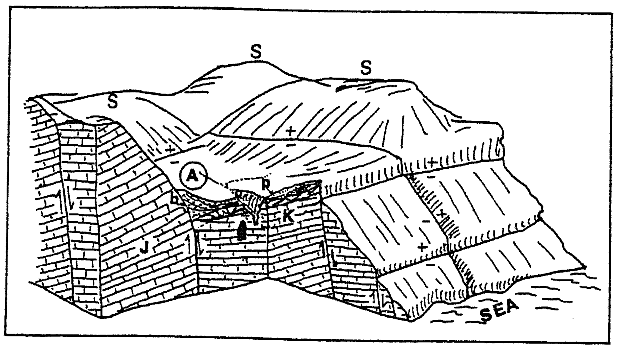

Figure 2. Geological block diagramm of the Furore area (modified from Aprile et al., 1978) showing the graben setting of the Agerola plain (A) and the location of the large cave. Key: S= remnants of the Pliocenic low-gradient erosion surface; p= piroclastic deposit; b= cryo-clastic deposit; K= Cretaceous limestone; J= Jurassic limestone.

Diagramma a blocco schematico dell'area di Furore (modificato da Aprile et al., 1978): S = resti della superficie a bassa energia pliocenica; p = depositi piroclastici; b = depositi crio-clastici; K = calcari cretacei; J = Calcari giurassici.

landscape. This old-age landscape is interpreted as the result of a poliphasic cycle of planation which occurred from Messinian to Pliocene (Brancaccio & Cinque, 1988, Aucelli et al., 1996). Remnants of this surface are

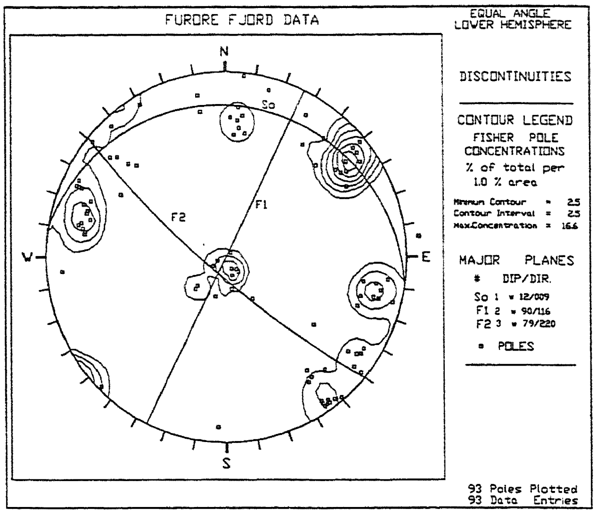

Figure 3. Pole and counter plot of bedding plane (So) and fracture systems (F1, F2) surveyed in the Jurassic limestone.

Diagramma polare ed isopunte della stratificazione (So) e dei sistemi di frattura (F1, F2) nei calcari giurassici.

the rounded summit crests, bounding the Agerola plain at 900-1000 m a.s.l..

Early Pleistocene block-faulting resulted in tilted and lifted blocks, the Agerola plain representing a down-lifted one forming, in the early stage, a centripetal drained karst basin (Aprile *et al.*, 1978). During Pleistocene, cryo-clastic deposit originated talus from the fault scarps facing the Agerola plain (Brancaccio & Cinque, 1988). In the Middle Pleistocene a new intensive block-faulting phase resulted into the southern highland sunk below the sea level, opening the Agerola basin towards the Thyrrenian Sea (Brancaccio & Cinque, 1988). The following uplift of the whole peninsula resulted in the progressive erosion of the fault scarp and the incision of the deep canyon of Furore (Aprile *et al.*, 1978, Cinque & Romano, 1990).

At present, the Furore valley is one of the most incised in the Amalfi coast. The hydrologic feed area is the Agerola plain, which drains the runoff waters of a mountain basin of about 13.5 km². The canyon begins at the elevation of 550 m a.s.l. with a narrow entrenchment in the cryo-clastic deposit. The valley, deepening between steep slopes and walls, cuts the Cretaceous and the Jurassic limestone, with a spectacular canyon descending till the sea level. The canyon continues below the present sea level, forming a narrow mouth known as "Furore fjord", partially filled by sand and gravel.

The rock slopes of Furore valley show some steps controlled by lithologic factors (fig.4). From the rim of the upper plain, at about 600-650 m a.s.l., there is a first step in correspondence of the overthrust surface at the base of Cretaceous limestone, which runs at about 480-500 m a.s.l.. The step forms a narrow bench, with undercut notches and small caverns, overhung by cliffs, arches and crevices, cut into the Cretaceous limestone. Downward, the slopes where Jurassic limestone outcrops, have a composite step-profile with steep slopes interrupted by cliffs some ten meter high. These walls overhang layers of more fractured rock (breccia bodies), conformable or not, in the Jurassic

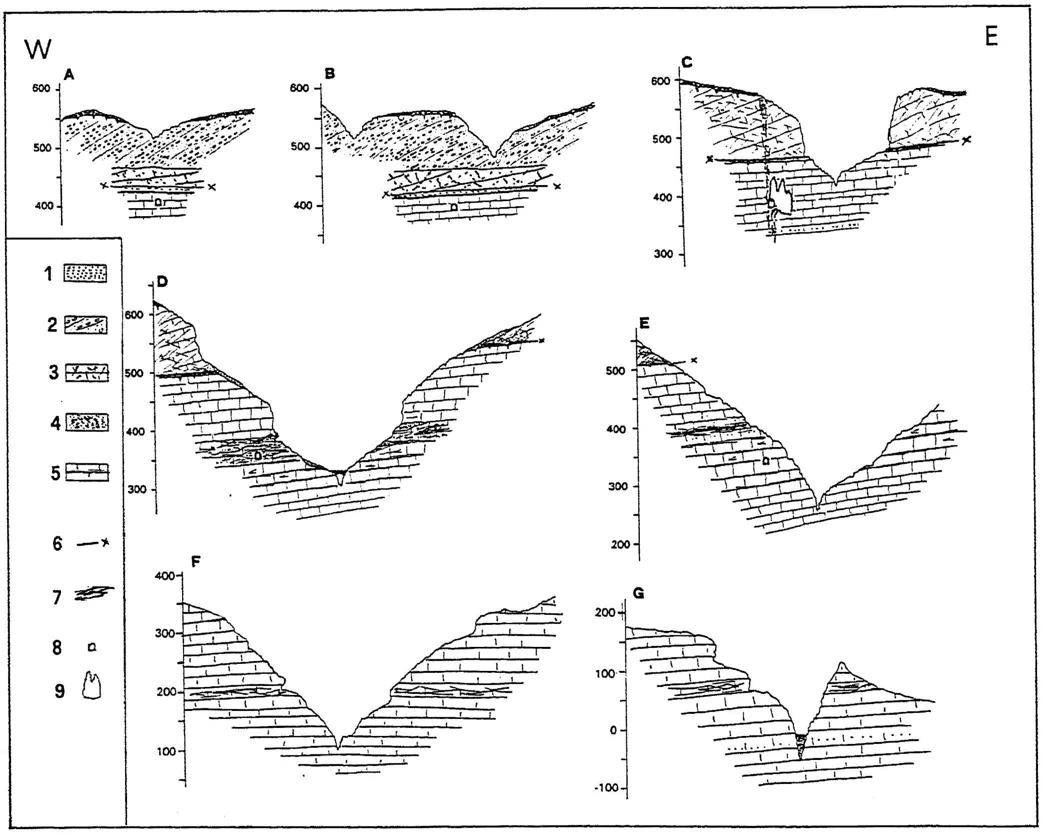

Figure 4. Cross-sections cut across the Furore canyon from the Agerola plain (section A) down to the sea (section G). Key: 1 = piroclastic deposit; 2 = cryo-clastic deposit; 3 = Cretaceous limestone; 4 = clastic deposit; 5 = Jurassic limestone; 6 = thrust plane; 7 = breccia bodies within the Jurassic limestone; 8 = water-pile tunnel; 9= cave.

Sezioni seriate attraverso il Vallone di Furore, dalla piana di Agerola (sezione A) fino al mare (sezione G): 1 = depositi piroclastici; 2 = depositi crio-clastici; 3 = calcari cretacei; 4 = depositi clastici; 5 = calcari giurassici; 6 = piano di thust; 7 = corpi di brecce nei calcari giurassici; 8 = tunnel idraulico; 9 = cavità carsica.

limestone. In correspondence of this layers, caves and undercut notches are frequently visible; their origin is mainly by selective weathering and collapse, and only locally by karst processes. Some of these steps resemble old wave-cut rock benches.

On the lower part of the cliff, old shorelines are visible at about 180-200, 45-50 and 8-10 m a.s.l.. These ancient shorelines form long horizontal wave cut notches in the cliff not following the bedding, which is gently dipping towards NW. Coastal deposit are locally preserved at the elevation of about 200 and 120 m a.s.l., mainly as filling of old coastal caves; the shoreline at 8-10 m a.s.l. can be related with beach deposit 130.000 years old (Brancaccio et al., 1978).

4. KARST

The whole Sorrentine Peninsula is a wide carbonate area of Mesozoic limestone where surface karst features are rare because neotectonics events deeply managed the landscape more than karst; also endokarst is not well known because of the absence of large detectable caves.

The geologic and morphologic setting of the Sorrentine Peninsula (carbonate rock, with sub-horizontal bedding, cut by deep valleys) is favourable to karst development. In spite of this, in the Agerola-Furore area, only some surface karst forms occur and only few caves are known, whereas the development of endokarst is emphasised by hydrogeologic features. In fact the drainage of waters is mainly by underground paths, towards large off-shore springs located in correspondence of the main tectonic lineaments (Celico, 1978).

In the Furore valley, small scale surface karst landforms are well developed only near the rim of the cliffs which cut the Agerola plain towards south, and where piroclastic deposit has been eroded. Here typical solution sculptures of humid-temperate karst, as rillenkarren, rundkarren, solution pits and small percolation holes, occur on the Cretaceous limestone. Small areas with small-scale solution sculptures (rillenkarren, kamenitza and residual ridges) are located in the rock terraces along the slopes of Furore valley.

The several caverns visible on the cliff of the valley are not the entrances of karst caves but mainly the product of weathering, which acts in correspondence of the more fractured rock. Some large caves visible on the lower part of the valley seem to be relict caves filled with breccia; these caves could be remnants of an ancient underground system which drained the waters of the Agerola basin towards the sea during the Late Pleistocene uplift of the Sorrentine Peninsula.

In the area, the only important cave with a natural entrance is the *Grotta di Santa Barbara*, opened in the fractured Cretaceous limestone, at an elevation of 580 m a.s.l., just below the cliff which truncates the Agerola plain. This cave has been interpreted by Brancaccio et al. (1976) as a relict-cave formed by the collapse of a large passage, part of a karst system draining the water of the southern relief towards the Agerola basin, before the Pleistocene block-faulting.

During the excavation of the water-pipe several caves were encountered; most of them are active small percolation caves formed along the main fractures. In the lower tunnel, at about 50 m a.s.l. there are a few small strata-bound caves with an irregular shape typical of no-gravity circulating caves; they originated in the phreatic-mixing zone when the sea was above this level.
In winter 1994, during the excavation of the higher tunnel, an unknown and unsuspected large cave (fig.5) was discovered at an elevation of 360 m a.s.l.. The cave has the shape of a chamber 20 m wide, 40 m long and about 50 m high. Its origin resulted from the coalescence of two percolation shafts. The oldest shaft develops

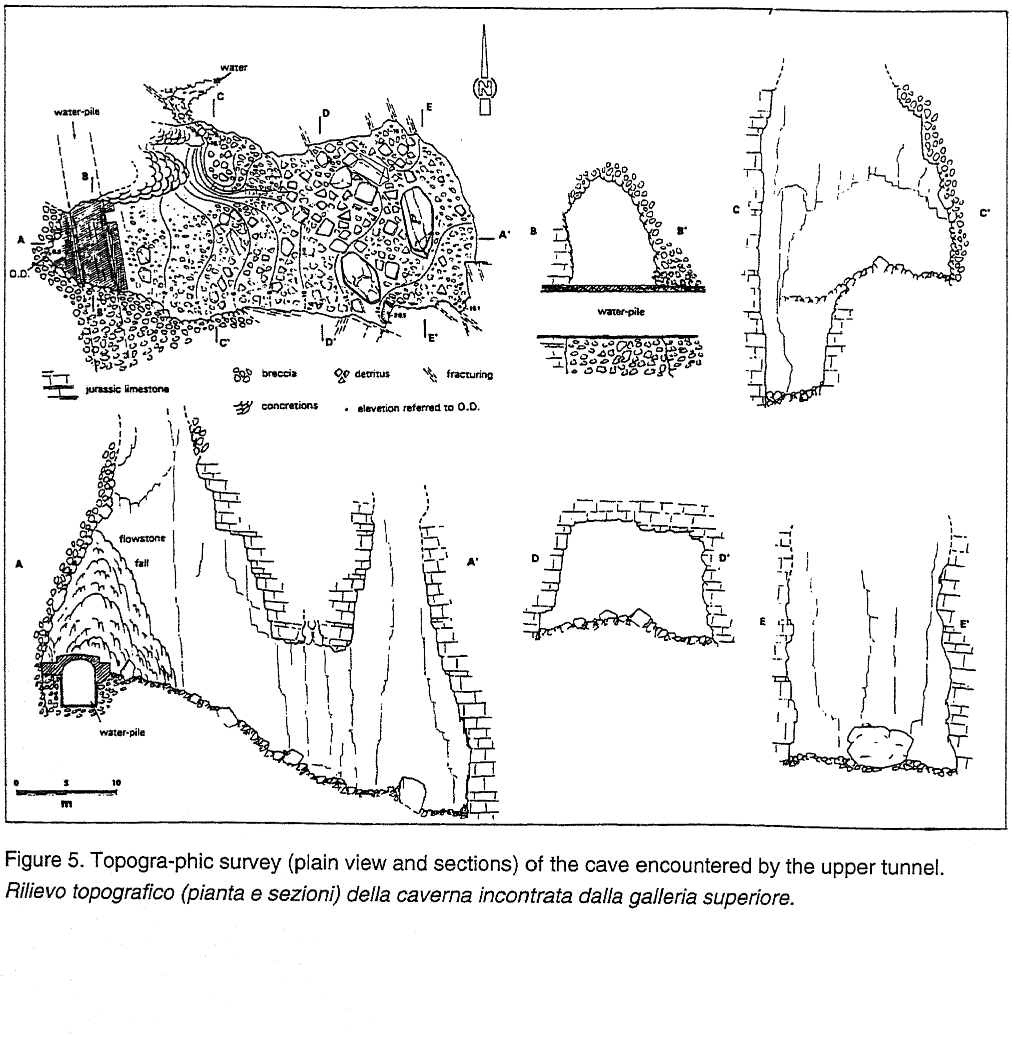

Figure 5. Topogra-phic survey (plain view and sections) of the cave encountered by the upper tunnel.
Rilievo topografico (pianta e sezioni) della caverna incontrata dalla galleria superiore.

in the western part of the chamber, in correspondence of a sub-vertical band, NW-SE oriented, of cohesive cataclasite. Some vertical bodies of *"in situ"* collapse breccia are probably related to the release stress occurred near the scarp formed by the Pleistocene faulting which led to the sinking of the southern side of the carbonate highland. In the eastern side of the chamber, another solution chimney develops along the cross of NW-SE and NNW-SSE fractures. The joint of the two shafts is relatively recent and is due to the collapse of the interposed rock-wall. Further ceiling block-falls widened the cave to the present shape.

The west side of the chamber is covered by calcite speleothemes, the most spectacular of which is a flowstone more than 15 m high.

5. EVOLUTION OF KARST EVENTS

Limestone outcrops in the Furore valley display a polycyclic karst evolution strongly controlled by neotectonics. According to the outlined morphotectonic history of the Sorrentine Peninsula the sequences of the main karst stages can be summarised as follows (fig.6).

1 - A first stage of karst occurred during the onset of the Jurassic carbonate platform.

2 - A successive longer stage of karst affected Jurassic limestone during pre-Miocene emersion. The breccia bodies, conformable or not, interlayered in the Jurassic limestone, which display all the karst features described by Sando (1988), Sangster (1988) and Kahle (1988) (fig.7), can be related to this paleokarst event,

3 - Neokarst evolution begins in the Pliocene, during the development of the low-gradient erosion surface; the *terra rossa* in-fills and the brown residual deposit discovered in small caves encountered during the excavation of the tunnel can be ascribed to this important pre-neotectonics stage. The origin of the *Grotta di S. Barbara* could be referred to the final phase of this stage, when the Agerola depression basin acted as a closed basin with underground drainage (Brancaccio et al. 1976). During Pleistocene block-faulting the ancient karst systems were disconnected and truncated by faults, remnants of these are visible in the cliffs of the

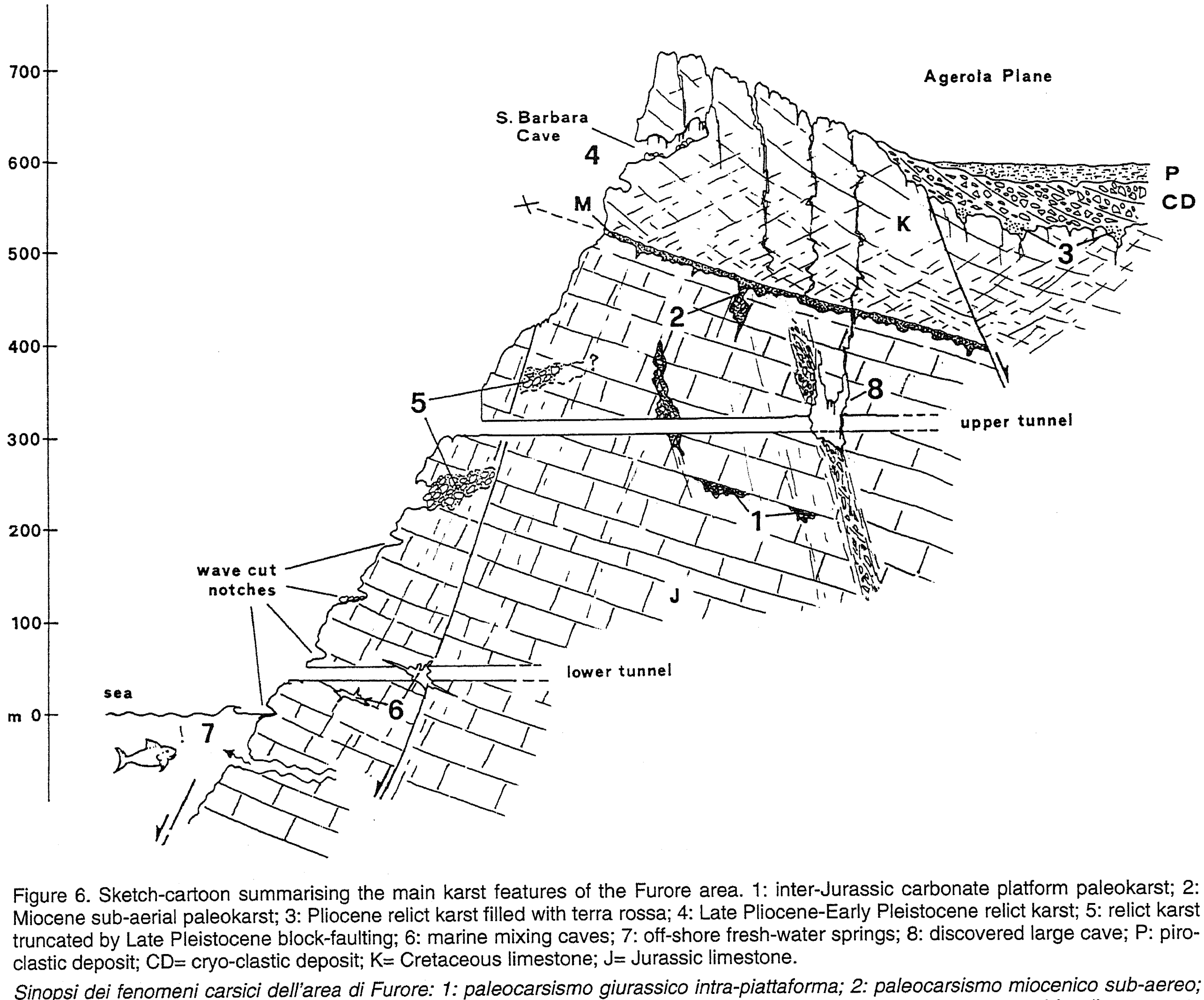

Figure 6. Sketch-cartoon summarising the main karst features of the Furore area. 1: inter-Jurassic carbonate platform paleokarst; 2: Miocene sub-aerial paleokarst; 3: Pliocene relict karst filled with terra rossa; 4: Late Pliocene-Early Pleistocene relict karst; 5: relict karst truncated by Late Pleistocene block-faulting; 6: marine mixing caves; 7: off-shore fresh-water springs; 8: discovered large cave; P: piroclastic deposit; CD= cryo-clastic deposit; K= Cretaceous limestone; J= Jurassic limestone.

Sinopsi dei fenomeni carsici dell'area di Furore: 1: paleocarsismo giurassico intra-piattaforma; 2: paleocarsismo miocenico sub-aereo; 3: forme carsiche relitte plioceniche riempite di terra rossa; 4: carsimo del tardo Pliocene-inizio Pleistocene; 5: cavità relitte troncate tagliate dalla tettonica tardo pleistocenica; 6: carsismo marino di miscelazione; 7: sorgenti a mare d'acqua dolce; 8: grande caverna; P= depositi piroclastici; CD= depositi crio-clastici; K=calcari cretacei; J= calcari giurassici.

Furore canyon as large caves filled with collapse breccia.

4 - Later stages of neo-karst occurred as tectonics block-faulted and uplifted, step by step, the whole area in respect to the sea level; this resulted into dissolution-enlarged fractures, small caves and dissolution voids. The large cave discovered in the tunnel has been developing during this karst stage by dissolution enlargement of a fracture band of cataclasite and breccia, and successively by the collapsing of coalescent caves.

5 - The development of several small phreatic caves, visible in the lower tunnel, can be related to the mixing of continental fresh waters with sea waters, when the sea level was higher than now. The submarine springs developed during the Wurmian low eustahic stage in correspondence of ancient shoreline.

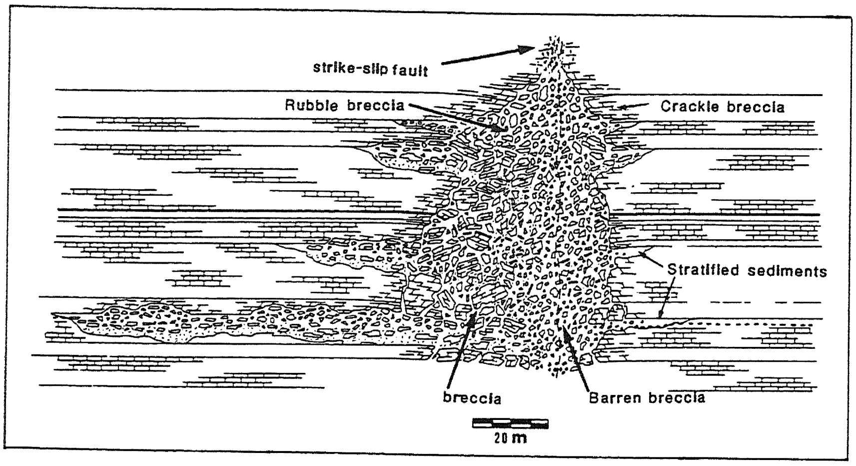

Figure 7. Feature of paleo-karst breccia body fault related and strata-bounded (modified from Sangster, 1988); the breccia bodies, conformable or not layered, in the Jurassic limestone display the same features.

Caratteristiche dei corpi di breccia lagati a carsimo interstratale e di faglia (modificato da Sangster, 1988); i corpi di breccia interni ai calcari giurassici presentano le stesse caratteristiche.

RINGRAZIAMENTI

We thank the Comune di Furore and the Recchi Costruzioni Generali s.p.a. for the technical and logistic support and C.Bartolini for the review of a preliminary version of the paper. This work was supported by C.N.R., Centro di studio per la geologia dell'Appennino e delle catene peri-mediterranee, Firenze, pubbl. n. 319.

REFERENCES

F. Aprile, L. Brancaccio, G. Carannante, E. Cravero, A. Cinque, S. Di Nocera, M. Guida, G. Iaccarino, F. Ortolani, T. Pescatore, I. Sgrosso & M. Torre (1978) - *Dati preliminari sulla neotettonica dei Fogli 172 (Caserta), 185 (Salerno), 196 (Sorrento) e 197 (Amalfi).* C.N.R., Prog. Fin. Geodinamica, Pubbl. 155, Roma, 85-112.

P.P.C. Aucelli, A. Cinque & D. Merola (1996) – *Discriminazione cronologica di eventi deformativi fragili lungo il margine settentrionale dei Monti Lattari sulla base di dati geologici e geomorfologici.* Il Quaternario, **9** (1), 319-324.

L. Brancaccio, G. Capaldi, A. Cinque, R. Pece & I. Sgrosso (1978) – *Th/U dating of corals from a tyrrhenian beach in Sorrentine Peninsula (Suthern Italy).* Quaternaria, **20**, 175-183.

L. Brancaccio & A. Cinque (1988) - *L'evoluzione geomorfologica dell'Appennino Campano-Lucano.* Mem. Soc. Geol. It., **41**, 83-86.

L. Brancaccio, A. Cinque & I. Sgrosso (1976) - *La Grotta di S. Barbara nel contesto della evoluzione geomorfologica della Piana di Agerola (Penisola Sorrentina).* Annuario Spel. CAI Napoli, **3**, 7-16.

F. Capotorti & M. Tozzi (1991) - *Tettonica trascorrente nella Penisola Sorrentina.* Mem. Soc. Geol. It., **47**, 235-249.

P. Celico (1978) - *Schema idrogeologico dell'Appennino carbonatico centro-meridionale.* Mem. e Note Ist. Geol. Appl. di Napoli, **14.**

A. Cinque (1980) - *Il sovrascorrimento di Monte Faito-Agerola (Penisola Sorrentina).* Boll. Soc. Natur. in Napoli, **90**, 89-117.

A. Cinque & P. Romano (1990) – *Segnalazione di nuove evidenze di antiche linee di riva in Penisola Sorrentina (Campania).* Geogr. Fis. Din. Quat., **13**, 23-36.

B. D'Argenio, A. Ietto & J.S. Oldow (1986) - *Low angle normal faults in the Monti Picentini, Southern Apennines.* Rend. Soc. Geol. It., **9**, 113-122.

C.F. Kahle (1988) - *Surface and subsurface paleokarst, Silurian Lockport, and Peebles Dolomites, Western Ohio.* In: Paleokarst (N.P. James & P.W. Choquette, Eds.). Springer-Verlag, New York, 229-255.

F. Ortolani (1978) - *Alcune considerazioni sulle fasi tettoniche Mioceniche e Plioceniche dell'Appennino Meridionale.* Boll. Soc. Geol. It., **97**, 609-616.

T. Pescatore & F. Ortolani (1973) - *Schema tettonico dell'Appennino Campano-Lucano.* Boll. Soc. Geol. It., **92**, 453-472.

W.J. Sando (1988) - *Madison limestone (Mississipian) paleokarst: a geologic synthesis.* In: Paleokarst (N.P. James & P.W. Choquette, Eds.). Springer-Verlag, New York, 256-277.

D.F. Sangster (1988) - *Breccia-hosted lead-zinc deposit in carbonate rocks.* In: Paleokarst (N.P. James & P.W. Choquette, Eds.). Springer-Verlag, New York, 102-116.

I. Sgrosso (1971) *Carta geologica d'Italia: Note illustrative dei fogli 185 e 197 Salerno e Amalfi.* Serv. Geol. It., Roma,38 pp.

Ms: ricevuto il: 14 aprile 1996
Inviato all'A. per la revisione il: 18 settembre 1996
Testo definitivo ricevuto il: 14 gennaio 1998

Ms received: April 14, 1996
Sent to the A. for a revision: September 18, 1996
Final text received: January 14, 1998