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KARSTIC LANDSCAPE EVOLUTION OF SOUTHERN APULIA FORELAND DURING THE PLEISTOCENE

ABSTRACT: SELLERI G., *Karstic landscape evolution of southern Apulia foreland during the Pleistocene*. (IT ISSN 1724-4757, 2007).

The Salento area is a narrow peninsula composed of Cretaceous and Neogenic carbonatic rocks constituting the southernmost part of the emerged Apulian foreland. A karstic landscape shaped on Upper Cretaceous – Lower Pleistocene rocks and covered by Middle Pleistocene terrigenous sediments has been recognized. The evolution of this karstic landscape was most likely promoted by new structural and geomorphological conditions due to the end of Apenninic orogenesis as well as eustatic sea level changes that occurred between the end of the Lower Pleistocene and the beginning of the Middle Pleistocene. During this period, in fact, the lowering of regional base level and a tectonic phase marked by NE-SW trending distensive structures occur. Afterwards, the karstic landscape was covered by a Middle Pleistocene marine terrigenous unit and during the last part of the Quaternary, partly re-exhumed and re-activated. The sequence of these phases has been controlled and influenced by structural changes occurred in the region.

Presently, the Salento Peninsula landscape shows at its inner and western parts wide karstic surfaces, remnants of the Middle Pleistocene sedimentary cover, and morphostructural ridges. The karstic surfaces are re-exhumed parts of the karstic landscape shaped between the Lower and the Middle Pleistocene. The morphostructural ridges are made of Mesozoic dolomitic-carbonatic units and show a policyclic landscape. Lastly, a number of young marine surfaces bordered by denudative scarps are shaped on the Middle Pleistocene sedimentary cover.

KEY WORDS: Karst, Marine terraced deposits, Salento, Apulia (Italy).

RIASSUNTO: SELLERI G., *Evoluzione del paesaggio carsico della Puglia meridionale durante il Pleistocene*. (IT ISSN 1724-4757, 2007).

In diverse località del Salento interno ed occidentale è identificabile un paesaggio carsico modellato su rocce di età compresa tra il Cretaceo superiore ed il Pleistocene inferiore, fossilizzato da sedimenti terrigeni del Pleistocene medio. Il modellamento di questo paesaggio è avvenuta tra la fine del Pleistocene inferiore e la parte iniziale del Pleistocene medio ed è stata favorita dalle nuove condizioni geomorfologiche e strutturali che ha assunto la parte meridionale dell'avampaese apulo con la fine dell'orogenesi appenninica. Durante questo intervallo di tempo, infatti, l'avampaese è stato interessato da un abbassamento del livello di base e da regime distensivo con direzione di massima estensione orientata NE-SW. Successivamente il paesaggio carsico è stato fossilizzato da coperture marine terrigene e, nel corso dell'ultima parte del Quaternario, discontinuamente riesposto e riattivato.

La successione di questi eventi, controllata e condizionata dalla evoluzione dell'assetto strutturale e geomorfologico regionale, ha portato la parte interna ed occidentale della penisola ad assumere il suo assetto attuale, caratterizzato da estese aree carsiche corrispondenti a lembi riesumati del carso modellato tra la fine del Pleistocene inferiore e l'inizio del Pleistocene medio, da lembi della originaria copertura sedimentaria medio pleistocenica e da rilievi morfostrutturali, denominati localmente «Serre», dove è esposto un paesaggio antico policiclico modellato sulle unità carbonatico-dolomitiche mesozoiche.

TERMINI CHIAVE: Carso, Depositi marini terrazzati, Salento, Puglia.

INTRODUCTION

The Salento region is a narrow and low elevated peninsula which constitutes the southernmost part of the emerged Apulian foreland. The landscape is made of different morphological units produced by the complex geomorphological evolution of this region. During the Neozoic, in fact, it occurred several times that a karstic landscape shaped during a morphogenetic phase was fossilized by a following phase marked by marine sedimentation or that ancient surfaces were re-exhumed during continental phases.

The Salento landscape is subsequentely compound of different areas marked by peculiar geomorphological features produced during distinct morphogenetic phases.

Very few data can be found in literature about the karstic morphogenetic phases occurred in the Salento region. In fact, even if the Paleogene phase is well known, the more recent and Quaternary phases have not been

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identified yet notwithstanding they are responsible for the most evident landforms in the Salento karstic landscape.

Cotecchia & Dell'Anna (1959) and Crescenti & Vighi (1967) produced the first papers about the Paleogene phase. These Authors studied the bauxite deposits that mantle two continental surfaces occurring inside and at the top of Mesozoic dolomite-limestone basement. In the Salento Peninsula the most recent of these surfaces crops out; it is referred to the Paleogene since it is fossilized by Oligocene and Miocene marine carbonatic units. Small remnants of this surface are well exposed at the top of morphostructural ridges occurring in the inner and eastern part of the peninsula and are marked by the presence of tropical karstic landforms.

New recent data allowed the sequence of morphogenetic phases to be integrated with the tectonic and stratigraphic evolution of the Salento peninsula. For example, Marsico & *alii* (2003) recognized along the Adriatic coast of southen Apulia remains of krypto-karstic landforms and proposed a geomorphological model for the genesis and evolution of these landforms taking into account the stratigraphic, tectonic, climatic conditions as well as sea level changes occurred in this area since the end of the Middle Pleistocene.

In this paper new data which allow to improve the definition of Salento geomorphological evolution during the Quaternary are reported. A new karstic morphogenetic phase has been recognized as well as the geomorphological evolution of inner and western parts of the peninsula has been defined in great detail.

GEOLOGICAL AND STRATIGRAPHICAL SETTING

The Salento region is the southernmost part of Apulian foreland made of a thick carbonatic basement which comprises different units whose age ranges from the Upper Cretaceous to the Lower Pleistocene. These units are covered by diffuse thin marine terrigenous sediments referred to the Middle-Upper Pleistocene (fig. 1).

The Cretaceous units are the upper part of the Campanian-Maastrichtian carbonatic sequence belonging to the Apulian carbonate platform which is several kilometres thick (Bosellini & Parente, 1994). More recent phases of marine sedimentation occurred between the Eo-Oligocene and the Lower Pleistocene. The most recent one produced at the end of the Lower Pleistocene the deposition of bioclastic calcarenites shading toward the Taranto Gulf into grey-bluish clayey marls. According to Ciaranfi & *alii* (1988) and Tropeano & *alii* (2005) this sedimentary event would be referable to the Fossa Bradanica cycle.

The terrigenous covers of Upper-Middle Pleistocene age are up to 15-20 meters thick and are indicated as Marine terraced deposits (Ciaranfi & *alii*, 1988). These covers formed during several marine transgressions which most likely never affected the eastern and southern part of the

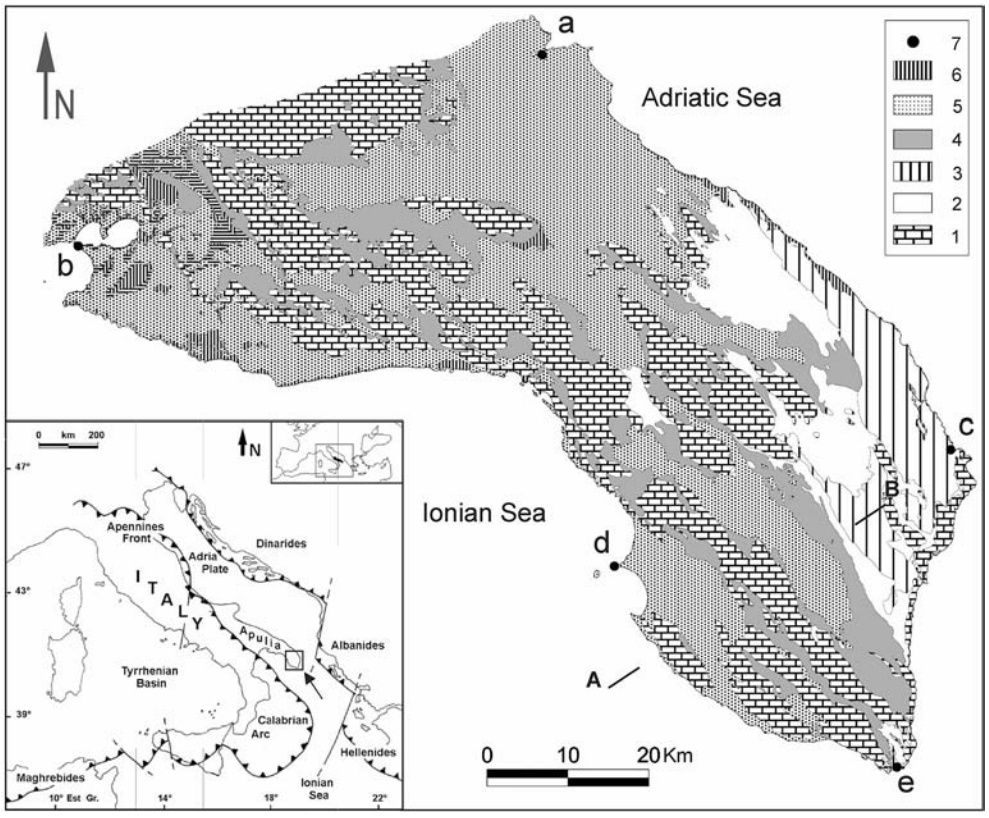

FIG. 1 - Schematic geological map of Salento peninsula. Legend: 1 Pre-Neogene dolomite-limestone units; 2 Middle-Upper Miocene limestones and calcarenites (Pietra leccese, Calcareniti di Andrai, Novaglie formations); 3 Upper-Middle Pliocene calcarenites, breccia and calcareous marls (Uggiano la Chiesa and Leuca formations); 4 Lower Pleistocene calcarenites (Calcarenite di Gravina formation); 5 Middle-Upper Pleistocene terrigenous deposits (Marine terraced deposits); 6 Recent and present marsh and beach deposits; 7 Main coastal localities: a - Taranto, b - Brindisi, c - Otranto, d - Gallipoli, e - Santa Maria di Leuca; A-B position of the geomorphological sketch reported in fig. 2.

Salento peninsula. The deposits cropping out along the coast stretching from Gallipoli to Taranto, referred to the end of Middle Pleistocene and to the Last Interglacial Period (Dai Pra & Stearns, 1977; Dai Pra, 1982; Hearty & Dai Pra, 1985; Hearty & *alii*, 1986; Dai Pra & Hearty, 1988; Hearty & Dai Pra, 1992), as well as the Middle-Upper Pleistocene sequence recognized at Pescoluse, between Gallipoli and Leuca (D'Alessandro & Massari, 1997) are the best known ones among the Marine Terraced Deposits. Several different units cropping out in other parts of the Salento peninsula are still poor studied.

In the inner part of the region the outcropping units are referable to the Middle Pleistocene (D'Alessandro & *alii*, 1987; D'Alessandro & *alii*, 1994). The complete stratigraphic sequence is composed at the base of massive yellow-greenish clayey sands, very rich in glauconite, and belonging to the Sabbie a Brachiopodi unit. The palaeontological assemblage of this unit marked by the presence of *Terebratula Scillae* Seguenza suggests a deposition depth greater than 100 m (D'Alessandro & Palmentola, 1978; D'Alessandro & *alii*, 1994). The Sabbie a Brachiopodi unit is covered by silty clays deposited in a shallower basin (Salvatorini, 1969; D'Alessandro & *alii*, 1994). An erosive contact divides this last unit from sandy silt made of quartz, micas, carbonatic fraction and scarce oligotypic fauna (mainly *Clamys* and *Ostrea*). The fauna as well as the sedimentological features would suggest that sedimentation occurred in shallow waters (Savatorini, 1969) but below the wave base. In the inner areas these deposits lay directly on the Mesozoic limestone and locally they shade upward into sandstones marked by carbonatic cement. Calcareous sandstones («Panchina»), up to 2 m thick, cover by means of an erosive contact the sandy silt or directly the underlying clayey silt deposits.

Very few data regarding the lithological units cropping out diffusely between Brindisi and Lecce are available (i.e. Radina, 1968; Ricchetti, 1972; Balenzano e De Marco, 1981; De Marco 1983). In this area, in fact, recent research has been carried out only on a Lower-Middle Pleistocene sequence cropping out along the Torre San Gennaro cliff (Coppa & *alii*, 2001).

The main tectonic phases that affected the Salento Peninsula occurred during the Eo-Oligocene, at the end of the Miocene, in the Middle Pliocene and during the first part of Middle Pleistocene (i.e. Letouzey & Tremolieres, 1980; Auroux e& *alii*, 1984; Bossio & *alii*, 1987a; Argnani & *alii*, 1993; Tozzi, 1993; Gambini & Tozzi, 1994). The last two phases were marked by a NE-SW trending distension (Auroux & *alii*, 1984; Bossio & *alii*, 1987b; Tozzi, 1993). Furthermore, the entire Apulian foreland has been interested by a general uplift since the Middle Pleistocene (i.e. Doglioni & *alii*, 1994) or the end of Lower Pleistocene (Pieri & *alii*, 1996; Tropeano & *alii*, 2002). According to Patacca & Scandone (1989) uplift was due to the break of the subducted slab and subsequent isostatic compensation of foreland. Doglioni & *alii* (1994) suggest that at the beginning of the Middle Pleistocene the thick continental lithosphere of the Apulian swell reached the Apenninic subduction hinge, offering increased resistance to the flexure. The subsequent slowing down of the eastward rollback of the subduction hinge and the penetration of the slab, induced the buckling of the Apulian foreland and the subsequent uplift of the region. Anyway, the cause of foreland uplift should be linked to the end of Apenninic orogenesis. In the Salento peninsula this uplift was not continuous as in the Murge area. During the Middle Pleistocene, in fact, a phase of pronounced subsidence occurred at least in the western and inner part of the peninsula and produced the deposition of deep water marine sediments (Sabbie a Brachiopodi unit). A phase of uplift was then responsible for the emersion of wide areas of the Salento peninsula. Recent studies (Mastronuzzi & *alii*, 2006) proved that the uplift stopped at MIS 9.3, about 330 ka BP. From this moment significant uplift rates have been recorded only in the Taranto area (Ferranti & *alii*, 2006).

THE KARSTIC LANDSCAPE

The Salento peninsula is a low elevated plain made of several wide surfaces placed between 150-160 m of altitude and the sea level (fig. 2). These surfaces are bordered by N-S, NW-SE and NNW-SSE partly degradated fault scarps or by scarps due to differential erosion (i.e. fault line scarps). The coastal area is marked by a staircase of marine terraces developed during the Middle-Upper Pleistocene (Palmentola, 1987; Ciaranfi & *alii*, 1994).

Wide depressed areas mark the inner and western parts of the peninsula which is characterized by Lower Pleistocene calcarenites outcroppings. These areas are bordered by the Middle Pleistocene terrigenous deposits as well as by the morphostructural highs where Apulia carbonatic platform units crop out. Wide depressions with complex shape and shallow dolinas partly filled up by some meters thick soil are the most widespread landforms. Dolinas show mainly circular or elliptic shape; they are rarely coalescent and with diameter ranging from 10 to more than 200 m. The spatial density of dolinas changes from area to area reaching the maximum value of 15 dolinas/km2. The speleological survey carried out during the last years points out the presence of complex karstic systems developed mainly along NW-SE, NNW-SSE directions. In the northwestern part of the peninsula also E-W and WNW-ESE directions have been recognized. The deepest caves of peninsula have been explored down to the karstic phreatic surface.

The morphostructural highs which border the Lower Pleistocene outcroppings are narrow ridges elongated in NW-SE direction, locally named «Serre». A subhorizontal surface roughly coincident with the geological structure constitutes the ridges top. However, a staircase of lithostructural plains characterizes the upper part of the most elevated highs as that one stretching from Galatone to Leuca reaching an elevation of 198 m. These surfaces are partly covered by continental deposits made at the base of residual clays and by aeolian quartz sands at the top. According to Palmentola (1987) short tracts of a relict hydrographic network can be still recognized on these surfaces.

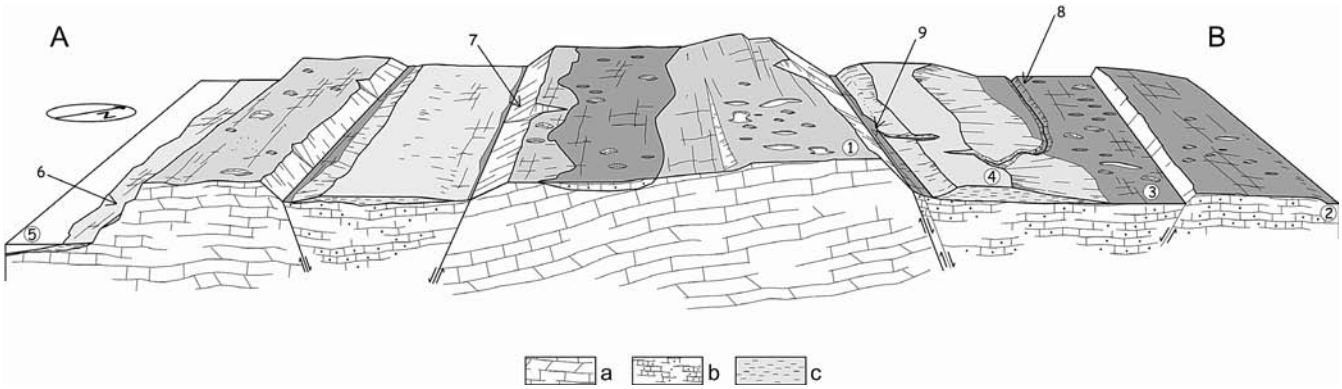

FIG. 2 - Geomorphological sketch of Salento peninsula between the «Serra di Castelforte» to the SW and the Maglie-Castiglione d'Otranto ridge (Serra degli Angeli) to NE (section A-B, fig. 1). The highest plains are the top surface of the morphostructural ridges (*Serre*) (1) shaped on the Cretaceous dolomite-limestone units, with the only exception of Serra degli Angeli (2). Slopes of these ridges are incised by short streams (7). The lowest plains are karstic surfaces (3) shaped on Neogene-Quaternary carbonatic units and areas where Middle-Upper Pleistocene terrigenous cover crops out (4). In these last areas several relict remnants of the Middle Pleistocene sediplain bordered by denudational slopes can be recognized. A drainage network (8) flowing toward a number of karstic sinkholes (9) is also detectable. The Ionian coastal area (5) is marked by a sequence of marine terraces (6). Legend: a - Cretaceous carbonatic units; b - Neogene-Quaternary carbonatic units; c - Middle-Upper Pleistocene terrigenous units.

The remnants of the relict marine surfaces emerged at the end of Middle Pleistocene due to a new phase of uplift have been recognized in the areas marked by marine terraced deposits outcroppings. These areas are bordered by differential erosion scarps or by degradated surfaces crossed by numerous endoreical drainage networks flowing towards the depressed areas characterized by Lower Pleistocene calcarenites outcroppings.

The areas at the inner and western part of Salento Peninsula where Lower Pleistocene calcarenites crop out are a clear example of contact karst (Selleri & *alii*, 2002). The formation and evolution of this type of karst is promoted by the presence of a contact (stratigraphic limit, tectonic contact, etc.) between carbonatic and not-carbonatic rocks (Gams, 1994; 2001). The main factors influencing the geomorphological evolution of these areas are the amount of allogenic waters and their chemical characteristics, the quantity and the grain size of solid load carried by the allogenic rivers, the permeability of carbonatic rocks, the local relief, the ratio between carbonate and not-carbonate areas and, lastly, the age of the karst (Gams, 1994). The contact karst of inner and western Salento is produced by the subhorizontal stratigraphic limit between the terrigenous, poor permeable Middle Pleistocene deposits which host a perched groundwater and the Lower Pleistocene calcarenites which represent in this area the carbonatic bedrock exposed at the bottom of shallow depressions. These geomorphological conditions promoted the flowing of a large amount of allogenic waters at the border of calcarenitic depressions enhancing karstic processes.

The landscape changes abruptly to the east of Maglie-Castiglione d'Otranto ridge, at the eastern part of peninsula. This sector has been most likely emerged since the beginning of the Pleistocene and is composed of different morphological units. Wide dolina fields affect the areas shaped on Pliocene calcarenites and marly calcarenites (Palmentola, 1987). A karstic landscape marked by a very low relief and wide depressions is recognizable in the areas where Miocene calcarenites and limestones crop out. Along the coast a surface showing large dolinas and low shield-like reliefs is shaped on different units belonging to the Eocene and the Oligocene. This surface is cut by the first and uppermost paleocliff of marine terrace staircase. Finally, on the top of morphostructural ridges where Mesozoic limestones crop out, the remains of a Paleogene karstic surface can be recognized.

THE NEW MORPHOLOGICAL AND STRATIGRAPHIC DATA

Karstic landforms fossilized by the Middle Pleistocene deposits have been recognized in numerous localities at inner and western Salento. These landforms are well exposed in the inner part of the peninsula, between the Cutrofiano and Tricase villages, in the surroundings of Santo Donno locality between Nociglia and Supersano villages, in the quarries placed close to the Aradeo, Novoli, Lequile, San Pietro and Veglie villages (fig. 3).

Cutrofiano-Tricase area

In this area the widest Lower Pleistocene calcarenites outcropping occurring in the innermost part of Salento peninsula has been surveyed. The area is bordered to the east by a low degradated fault scarp; it is NNW-SSE trending and about 20 km long. To the north a wide outcropping of Middle Pleistocene quartz-mica sandy silt occurs; along its margins several cover dolinas have been found.

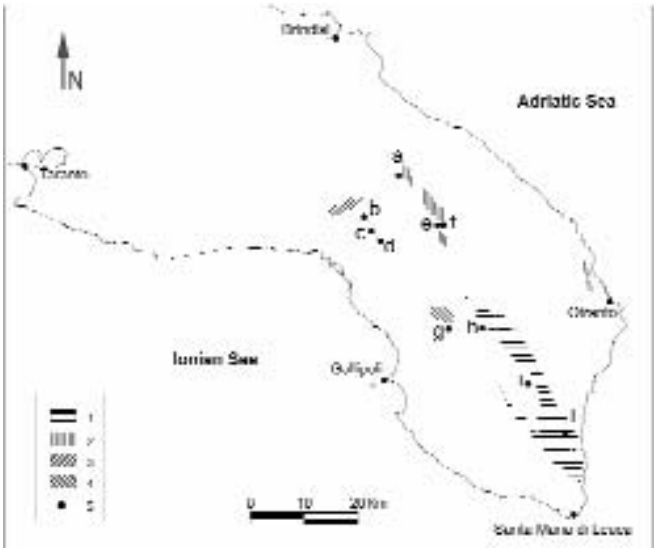

FIG. 3 - Geographical position of areas and localities where detailed surveys were carried out. Legend: 1 - Cutrofiano-Tricase area; 2 - Lequile, San Pietro, Novoli quarries area; 3 - Veglie quarries area; 4 - Aradeo quarries area; 5 - villages and localities: a - Novoli, b - Veglie, c - Le Vore, d - Leverano, e - San Pietro, f - Lequile, g - Aradeo, h - Cutrofiano, i - Santo Donno, l - Tricase.

The karstic surface shaped on the Pleistocene calcarenites is a flat plain, dipping towards NW; it is placed between 120 m of elevation along the coastal area and 40-50 m along its northern border. Its central and northern parts receive a large amount of surface waters from the areas where the Middle Pleistocene sandy silts crop out. Its southern part is higher in elevation and does not receive any flows of allogenic waters.

The karstic landscape is marked by the diffuse presence of dolinas with diameter up to 200 m and closed depressions up to some km^2 wide, elongated in NW-SE and NNW-SSE direction. The spatial density of dolinas can locally reach values of 14-15 dolinas/km^2. These landforms are filled with sediments so that they are not well expressed in the landscape. The complete sequence of the dolinas filling is made from the bottom to the top of (fig. 4):

– thin layers of reddish residual clays laying directly on the Lower Pleistocene calcarenites;
– yellowish sandy silt, mainly made of quartz and micas, up to 15 m thick, that can be referred to the Middle Pleistocene unit cropping out at the western margin of Cutrofiano-Tricase area;
– sandy-silty reddish paleosol, up to several meters thick, showing a coarse fraction made of oxides aggregates and quartz grains covered by oxide varnish;
– clayey-silty brownish soil, up to 1.5 m thick. The coarse fraction is similar to that one of underlying paleosol.

The shape of some dolinas has been reconstruct by means of geophysical surveys and boreholes. Shallow subcircular dolinas marked by an asymmetric cross profile, up to 50 m wide, have been individuated as well as sub-circular dolinas bordered by subvertical slopes, up to 60 m wide and 20 m deep.

Aradeo area

The village of Aradeo is placed at the northernmost part of quartz-mica sandy silt outcropping occurring in the Cutrofiano-Tricase area (fig. 3). The Lower Pleistocene carbonatic basement marked by endokarst landforms fos-

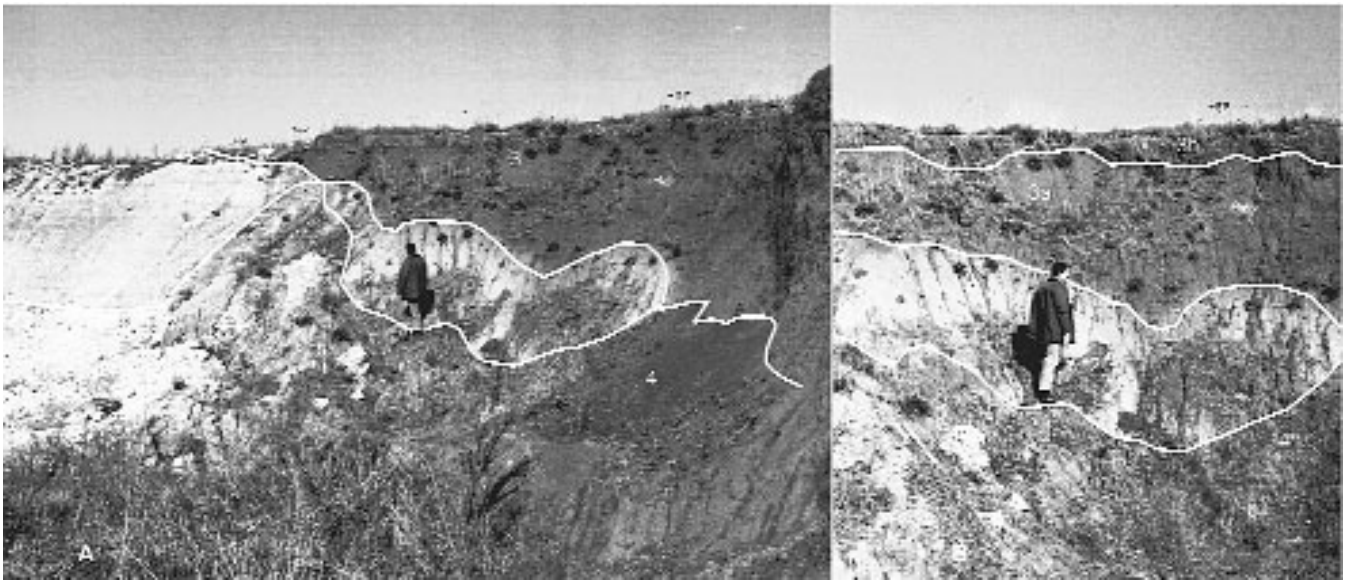

FIG. 4 - Doline buried by the Middle Pleistocene quartz-mica sandy silt partly exposed along a trench wall (Masseria Piccola, Spongano). Legend: 1 - Lower Pleistocene calcarenite; 2 - Middle Pleistocene quartz-mica sandy silt; 3 - soils (3a reddish paleosol, 3b brownish paleosol); 4 - Debris.

silized by the cover sediments is well exposed in several quarries occurring in the Aradeo area. The exposed caves develops along NW-SE and NNW-SSE directions, deepens below the quarry floor and some of them retain speleothems (fig. 5). Furthermore, along the quarry cliffs the contact of sandy silts on the Lower Pleistocene calcarenites is well exposed; it is marked by small dolinas and meter-scale cylindrical depressions (fig. 6).

Santo Donno locality (Nociglia)

The Santo Donno locality is placed along the western margin of quartz-mica sandy silts occurring at Cutrofiano-Tricase area (fig. 3). Here two adjacent cover dolinas, few meters deep and with an elliptic shape, have been found. The major axis of dolinas is of about 15-20 m; the minor axis is of about 10 m. In this locality the sandy silts are about 15 m thick and cover the Lower Pleistocene calcarenites. A perched groundwater is present in the area.

An electric tomography has been carried out at the border of the two depressions (fig. 7). A first layer with resistivity lower than 40 Ohm*m has been identified; it corresponds to the Middle Pleistocene sandy-silty cover. In this layer, lenses with higher or lower resistivity occur. The first ones represent the water layer which disappear near two sinkholes. The latter are small cemented levels inside the sandy silts. The layer marked by resistivity values lower than 40 ohm*m lays on a unit with higher resistivity that can be interpreted as the Lower Pleistocene carbonatic bedrock. The geophysical survey reveals a very irregular contact between the sandy-silty cover and the bedrock. It is characterized by wide depressions bordered by gentle slopes (flat dolina type) and large pits with vertical walls, more than 10 m deep. The fragmentation of the perched groundwater close to the sinkholes is most likely due to the drainage at the bedrock depressions. The low resistivity lens that point out the perched groundwater show, in fact, remarkable bends downward in correspondence of main buried karstic landforms.

FIG. 5 - Karstic cavity shaped into the Lower Pleistocene carbonatic bedrock buried by the Middle Pleistocene marine deposits exposed along a quarry wall at Petra Grossa locality (Aradeo); the contact is marked by a dashed line. The cavity has been partly emptied by quarry activity; along its walls some speleothems are preserved (B frame). Legend: 1 - Lower Pleistocene calcarenite; 2 - speleotheme; 3 - Middle Pleistocene marine deposits.

Lequile, Novoli and San Pietro area

Along this area of western Salento (fig. 3) the terrigenous marine deposits that cover the carbonatic bedrock are represented by the Sabbie a Brachiopodi formation

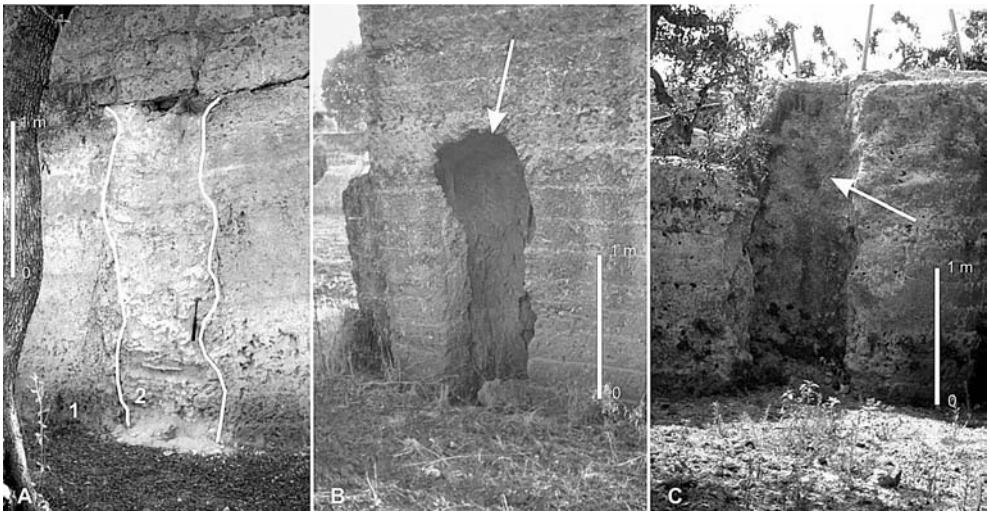

FIG. 6 - Vertical karstic cavities shaped into the Lower Pleistocene carbonatic bedrock exposed along quarry walls at Pietra Grossa locality (Aradeo). In A the cavity is still filled by the Middle Pleistocene sandy-silty marine deposits; in B and C cavities have been emptied due to quarry activity. Legend: 1 - Lower Pleistocene calcarenite; Middle Pleistocene quartz-mica sandy silt.

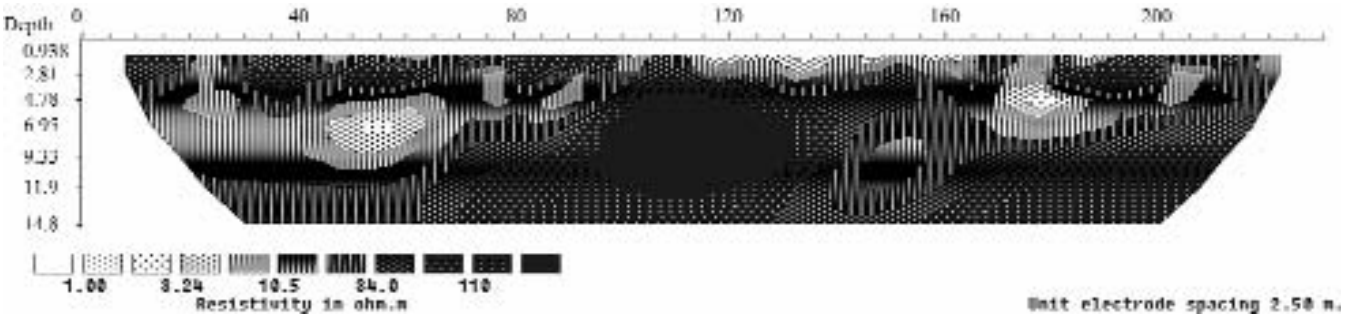

FIG. 7 - Resistivity model carried out near the two cover sinkholes placed at Santo Donno locality. The Lower Pleistocene carbonatic bedrock is marked by resistivity higher than 34 Ohm*m. The bedrock top surface is characterized by remarkable irregularities; in particular a pit depression more than 10 m deep has been detected between 60 m and 80 m of progressive distance. The Middle Pleistocene terrigenous cover is marked by resistivity lower than 34 Ohm*m. In this cover resistive bodies occur; they correspond to calcarenitic lens and conductive bodies due to the presence of a discontinuous perched groundwater. The survey was performed by using the georesistivimeter Syscal R1. Data elaboration was carried out by means of RES 2D INV software.

and by the overlying clayey-silty units. This sequence has been referred to the Middle Pleistocene (D'Alessandro & *alii*, 1994) and lays on the carbonatic bedrock which is locally made by the Lower Pleistocene calcarenitic units. The contact surface among the Middle Pleistocene covers, locally marked by paleosols, is exposed along the walls of the numerous quarries occurring in the area. This surface has a very irregular shape being marked by large funnel-shaped dolinas and deep cylindrical cavities. D'Alessandro & *alii* (1994) described these last landforms and attribute them to cavitation process produce by waves on shore platforms shaped on weak rocks.

Veglie-Leverano area

These two villages of western Salento (fig. 3) are placed along the limit between a large area where Sabbie a Brachiopodi formation crops out and the Cretaceous-Lower Pleistocene carbonatic rocks. The first area corresponds to the southern part of the Middle Pleistocene sediplain which is bordered by a slope dissecated by drainage network made of short streams flowing towards the area where the carbonatic bedrock crops out. In this last area dolinas and pits fossilized by the Sabbie a Brachiopodi unit are well exposed along quarry and trench walls (fig. 8).

The electric tomography has detected three levels (fig. 9). The lowermost level shows a resistivity higher than 60 ohm*m; it is the carbonatic bedrock compound by Upper Cretaceous limestones and by thin layers of Lower Pleistocene calcarenites. Upward a level marked by a resistivity of about 60 ohm*m point out the Middle Pleistocene terrigenous cover. Also this survey reveals the articulated surface occurring between the carbonatic bedrock and the cover deposits which is marked by flat dolinas and pits more than 20 m deep. The shallower level is marked by a resistivity of about 20 Ohm*m corresponding to the perched groundwater occurring into the Middle Pleistocene deposits. The lower surface of this level is marked by evident bulging downward where the

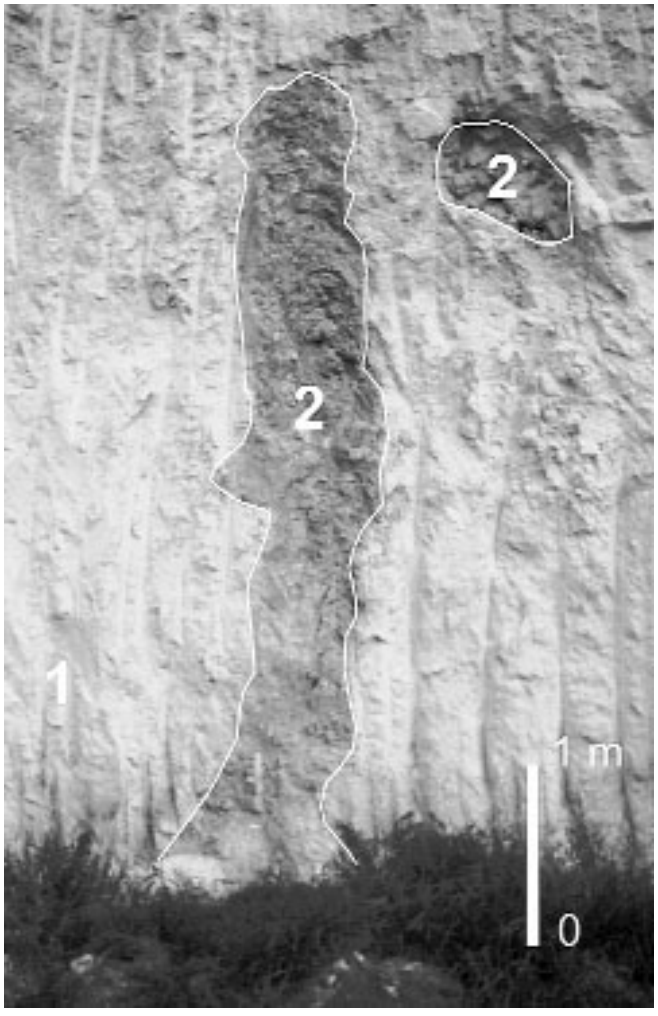

FIG. 8 - Karstic void shaped into the Lower Pleistocene carbonatic bedrock filled by the Middle Pleistocene marine deposits, exposed along a quarry wall in the surrounding of Veglie. Legend: 1 - Lower Pleistocene calcarenites; 2 - Sabbie a Brachiopodi formation (Middle Pleistocene).

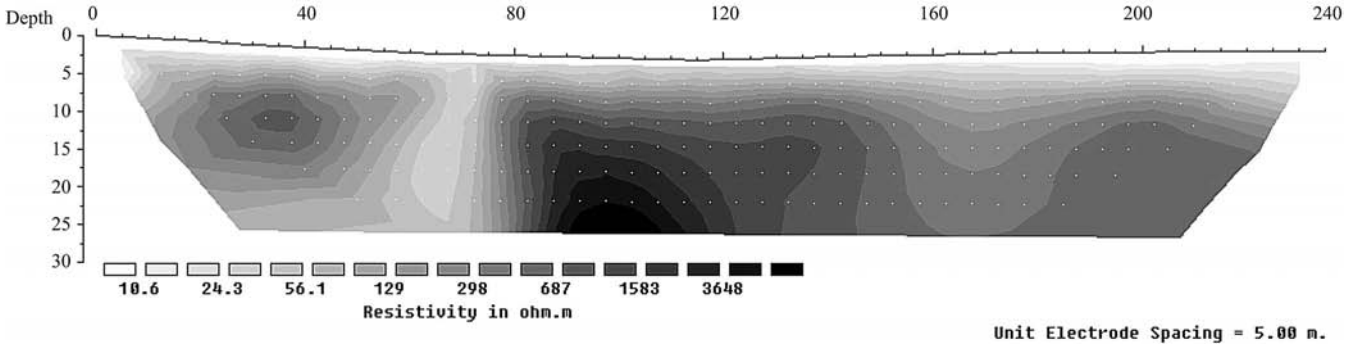

FIG. 9 - Resistivity model at Le Vore locality. The Upper Cretaceous limestones and thin lenses of Lower Pleistocene calcarenites is marked by resistivity higher than 50 Ohm*m. The Middle Pleistocene terrigenous cover shows values of resistivity of about 50 Ohm*m. The contact between the carbonatic limestone and the cover shows an irregular shape characterized by a pit depression (between 60 m and 80 m of progressive distance) and by a flat dolina (between 140 and 200 m of progressive distance). The shallower body, marked by resistivity of about 20 Ohm*m, corresponds to the perched groundwater occurring inside the Middle Pleistocene deposits. This body shows an inflexion downward between 60 and 80 m of distance probably due to the downward drainage along the buried cavity. The survey was performed by using the georesistivimeter Syscal R1. Data elaboration was carried out by means of RES 2D INV software.

carbonatic bedrock is affected by major depressions. This evidence suggests even in this case that the perched groundwater is drained in correspondence to the main buried cavities.

DISCUSSION

A relict karstic landscape covered by Middle Pleistocene marine terrigenous units is exposed at several localities of inner and western Salento. The Middle Pleistocene units often cover a surface shaped on the Upper Cretaceous – Lower Pleistocene carbonatic bedrock. This surface is marked by the diffuse presence of karstic landforms such as dolinas, kluftkarren, *etc.*, and by an endokarst fossilizied by a sedimentary cover. According to the chronological attribution of the bedrock and the cover reported in literature (D'Alessandro & Palmentola, 1978; Bossio & *alii*, 1987c; Ciaranfi & *alii*, 1988; D'Alessandro & *alii*, 1988; D'Alessandro & *alii*, 1992; D'Alessandro & Massari, 1997) the morphogenetic phase responsible for the shaping of the detected landforms can be placed between the end of the Lower Pleistocene and the beginning of the Middle Pleistocene.

During this period the Salento peninsula was marked by a tectonic regime with maximum extension NE-SW oriented (Martinis, 1962; Martinis, 1967; Palmentola & Vignola, 1980; Auroux & *alii*, 1984) and most likely by an increase of relief energy as a consequence of the stopping of Apenninic alloctonous nappes, the beginning of Apulian foreland uplift and the sea level low stand. In fact, according to Shackleton & *alii* (1990) e Shackleton (1995) the limit between the Lower and the Middle Pleistocene comprises the MIS 24, 23 and 22, all marked by a sea level low stand.

According to Quinif (1998) karst landscape development occurs during periods marked by a tectonic distensive regime and low sea level stand due to eustatic and /or tectonic causes which produce an increase of the hydraulic conducibility along joints and of the hydrodynamic potential. In the case of Salento peninsula, the occurrence of a distensive tectonic regime and of a relief between the end of the Lower Pleistocene and the beginning of the Middle Pleistocene promoted the development of a karstic landscape marked by a low local relief. This landscape is marked by the occurrence of large dolinas and depressions as well as a developed endokarst. Karst landforms mainly formed along NW-SE oriented joints in response to the NE-SW oriented extension stress.

This karstic morphogenetic phase has been interrupted by the Middle Pleistocene marine transgressions which produced the burying of the karstic landscape beneath a terrigenous, low permeable sedimentary cover. Afterward, the uplift of the Apulian foreland stopped most likely just before the MIS 9.3 (Mastronuzzi & *alii*, 2006) produced the emersion of wide areas. This last phase has been accomplished by the development of a drainage network and by the erosive re-exhumation of the Lower - Middle Pleistocene karstic landscape. The karstic landscape is well exposed in the southern and mid-southern sectors of Salento because of higher rate of uplift (Palmentola & Vignola, 1980). In the north-western and western sectors, marked by lower uplift rates (Palmentola & Vignola, 1980) the karstic landscape is still covered by the Middle-Upper Pleistocene marine sedimentary cover. D'Alessandro & *alii* (1994) estimated an uplift of about 150 m during this phase on the basis of the faunal assemblage of Sabbie a Brachiopodi unit.

According to Mastronuzzi & *alii* (2006) tectonic stability has been occurred at least at the southern part of Salento from MIS 9.3 up to present.

The re-exhumation of the karstic landscape has been accomplished by its local re-activation. The development of the drainage network, in fact, allowed the flow of a

large amount of surficial waters in the karstified areas promoting the re-activation of karstic systems. Where the karstic landscape is still covered by the Middle Pleistocene marine units the re-activation is scarce and linked mostly to the dynamics of perched groundwater.

The geomorphological evolution of Salento peninsula produced a typical example of contact karst. Three units compound this landscape:

– re-exhumed karstic landscape shaped into the Upper Createcous and Lower Pleistocene units;
– Middle Pleistocene marine sediplain transgressive on Upper Cretaceous - Lower Pleistocene carbonatic bedrock and bordered by denudative slopes;
– Morphostructural ridges corresponding to the outcroppings of Upper Cretaceous dolomite - limestone units. These ridges formed before the Lower Pleistocene (Palmentola & Vignola, 1980) and are marked by the lack of landforms belonging to the short morphogenetic phase occurred at the limit between the Lower and the Middle Pleistocene. The landscape could be older and most likely polycyclic as the occurrence of small remains of Paleogene karstic surface would suggest.

CONCLUSIONS

At several localities of Salento peninsula a karstic landscape covered in some places by Middle Pleistocene terrigenous units has been identified. The evolution of this landscape can be subdivided in three main phases: development, burying and re-exhumation accomplished by local re-activation of the karstic system.

The development of the karstic landscape is occurred in a relatively short period at the limit between the Lower and the Middle Pleistocene. This morphogenetic phase was promoted by a low stand of sea level and a tectonic phase with NE-SW oriented extension linked to the end of Apenninic orogenesis.

The karstic landscape was buried beneath the terrigenous marine sediments accumulated during some transgressive/regressive cycles occurred in the Middle Pleistocene.

Finally, the erosion of the marine cover produced the re-exhumation of the Lower-Middle Pleistocene karstic landscape and its re-activation. This last event has been controlled by the differential uplift of Salento peninsula which produced firstly the re-exhumation of the karstic landscape in the southern and innermost parts of the region during the Middle Pleistocene.

The sequence of these morphogenetic phases has been responsible for the present landscape occurring at the inner and western parts of the Salento peninsula. It is compound by three main units: the area where the Lower-Middle Pleistocene karstic landscape is exposed; the relict remnants of the Middle Pleistocene sediplain and the morphostructural ridges shaped on Cretaceous dolomite and limestone units. These last ones show an ancient polycyclic landscape with peculiar features very different from those ones of Lower-Middle Pleistocene age.

REFERENCES

ARGNANI A., FAVALLI P., FRUGONI F., GASPERINI M., LIGI M., MARANI M., MATTIETTI G. & MELE G. (1993) - *Foreland deformational pattern in the Southern Adriatic Sea*. Annali di Geofisica 36, 212-224.

AUROUX C., MASCE J., CAMPREDON R., MASCLE G. & ROSSI S. (1984) - *Cadre gèodynamique et évolution récente de la dorsale apulienne et des ses bordures*. Giornale di Geologia, 47, 101-127.

BALENZANO F. & DE MARCO A. (1981) - *La magnetite nei depositi pleistocenici di Francavilla Fontana (Brindisi). Considerazioni paleogeografiche.* Rendiconti della Società Italiana di Mineralogia e Petrologia, 37, 175-179.

BOSELLINI A. & PARENTE M. (1994) - *The apulian platform margin in the Salento peninsula (Apulia, Southern Italy)*. Giornale di Geologia, 56(2), 167-177.

BOSSIO A., GUELFI F., MAZZEI R., MONTEFORTI B. & SALVATORINI G. (1987a) - *Studi sul Neogene e Quaternario della penisola salentina. II - Evoluzione paleogeografica dell'area di Leuca nel contesto dell'area mediterranea.* Atti del Convegno sulle conoscenze geologiche del territorio salentino. Lecce 12 dicembre 1987. Quaderni di Ricerche del Centro Studi Geotecnici e di Ingegneria Lecce, 11, 31-54.

BOSSIO A., GUELFI F., MAZZEI R., MONTEFORTI B., SALVATORINI G. & VAROLA A. (1987b) - *Studi sul Neogene e Quaternario della penisola salentina. VIII - Sul riempimento di due fessure nella Pietra leccese dell'area di Cavallino.* Atti del Convegno sulle conoscenze geologiche del territorio salentino. Lecce 12 dicembre 1987. Quaderni di Ricerche del Centro Studi Geotecnici e di Ingegneria Lecce, 11, 195-205.

BOSSIO A., GUELFI F., MAZZEI R., MONTEFORTI B., SALVATORINI G. & VAROLA A. (1987c) - *Precisazioni sull'età dei sedimenti pleistocenici di due cave del leccese (San Pietro in Lama e Cutrofiano).* Quaderni di Ricerche del Centro Studi Geotecnica e di Ingegneria Lecce, 11 pp. 147-174.

CIARANFI N., PIERI P. & RICCHETTI G. (1988) - *Note alla carta geologica delle Murge e del Salento (Puglia centromeridionale).* Memorie della Società Geologica Italiana, 41, 449-460.

CIARANFI N., PIERI P. & RICCHETTI G. (1994) - *Linee di costa e terrazzi marini pleistocenici nelle Murge e nel Salento: implicazioni neotettoniche ed eustatiche.* Geologia delle aeree di avampaese. 77a riunione estiva della Società Geologica Italiana. Bari, 26-28 settembre 1994. Riassunti, 170-171.

COPPA M.G., DE CASTRO P., MARINO M., ROSSO A. & SANFILIPPO R. (2001) - *The Pleistocene with Aequipecten opercularis (Linneo) of «Campo di Mare» (Brindisi, Italy).* Bollettino della Società Paleontologica Italiana, 40 (3), 405-409.

COTECCHIA V & DELL'ANNA L. (1959) - *Contributo alla conoscenza delle bauxiti e terre rosse del Salento.* Memorie e note dell'Istituto di Geologia Applicata dell'Università di Napoli, VII, 5-20.

CRESCENTI V. & VIGHI L. (1964) - *Caratteristiche, genesi e stratigrafia dei depositi bauxitici cretacici del Gargano e delle Murge; cenni sulle argille con pisoliti bauxitiche del Salento (Puglia).* Bollettino della Società Geologica Italiana, 83, 285-338.

D'ALESSANDRO A., LOIACONO F. & RICCHETTI G. (1987) - *Note illustrative alla carta geomorfica del Salento meridionale (F.525 Gallipoli, 526 Nardò, 527 Otranto, 536 Ugento e 537 Capo S. Maria di Leuca).* Atti del Convegno sulle conoscenze geologiche del territorio salentino. Lecce 12 dicembre 1987. Quaderni di Ricerche del Centro Studi Geotecnica e di Ingegneria Lecce, 11, pp. 207-222.

D'ALESSANDRO A. & MASSARI F. (1997) - *Pliocene and Pleistocene depositional environments in the Pescoluse area (Salento, Italy).* Rivista Italiana di Paleontologia e Stratigrafia, 103(2), 221-258.

D'ALESSANDRO A., MASTRONUZZI G., PALMENTOLA G. & SANSÒ P. (1994) - *Pleistocene deposits of Salento leccese (Southern Italy): problematic relationships.* Bollettino della Società geologica Italiana, 33(2), 257-263.

D'ALESSANDRO A. & PALMENTOLA G. (1978) - *Sabbie a Brachiopodi, una nuova unità del Salento leccese (aspetti litostratigrafici e paleoambientali).* Rivista Italiana di Paleontologia e Stratigrafia, 84, 1083-1120.

DAI PRA G. & HEARTY P.J. (1988) - *I livelli del mare Pleistocenici del Golfo di Taranto. Sintesi geocronostratigrafica e tettonica.* Memorie dela Società Geologica Italiana, 41, 637-644.

DAI PRA G. (1982) - *The late Pleistocene marine deposits of Torre Castiglione (Southern Italy).* Geografia Fisica e Dinamica Quaternaria, 5, 115-119.

DAI PRA G. & STERNS C.E. (1977) - *Sul Tirreniano di Taranto. Datazione sui coralli col metodo del Th^{230}/U^{234}*. Geologica Romana, 16, 231-242.

DE MARCO A. (1982) - *Ricerche mineralogiche sui depositi quaternari di San Vito dei Normanni e di Latiano (Brindisi): applicazioni cronostratigrafiche.* Rendiconti della Società Italiana di Mineralogia e Petrologia, 38 (2), 857-869.

DOGLIONI C., MONGELLI F. & PIERI P. (1994) - *The Apulia Uplift (SE Italy): An anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere.* Tectonics, 13 (5), 1309-1321.

FERRANTI L., ANTONIOLI F., MAUZ B., AMOROSI A., DAI PRÀ G., MASTRONUZZI G., MONACO C., ORRÙ P., PAPPALARDO M., RADTKE U., RENDA P., ROMANO P., SANSÒ P. & VERRUBBI V. (2006) - *Markers of the last interglacial sea level high stand along the coast of the Italian Peninsula: tectonic implications.* Quaternary International, 145-146, 30-54.

GAMBINI R. & TOZZI M. (1994) - *Assetto tettonico della «piastra» apula e ipotesi sulla evoluzione cinematica mesozoica.* Geologia delle aeree di avampaese. 77ª riunione estiva della Società Geologica Italiana. Bari, 26-28 settembre 1994. Riassunti, 29.

GAMS I. (1994) - *Types of contact karst.* Geografia Fisica e Dinamica Quaternaria, 17, 37-46.

GAMS I. (2001) - *Notion and forms of contact karst.* Acta Carsologica, 30(2), 33-46.

HEARTY P.J, BONFIGLIO L., VIOLANTI P. & SZABO B.J. (1986) - *Age of Late Quaternary marine deposits of Southern Italy determined by aminostratigraphy, faunal correlatin and uranium series dating.* Rivista Italiana di Paleontologia e Stratigrafia, 92(1), 149-164.

HEARTY P.J.& DAI PRA G. (1985) *Aminostratigraphy on Th^{230}/U^{234} deating of Quaternary shorelines in the Puglia region of Southeast Italy.* Proccedings of the Fifth International coral Reef Congress, Thaiti, 3, 163-169.

HEARTY P.J. & DAI PRA G. (1992) - *The age and stratigraphy of middle Pleistocene and younger deposits along the Gulf of Taranto (Southeast Italy).* Journal of Coastal Research, 8(4), 82-105.

LETOUZEY J. & TREMOLIERE S. (1980) - *Paleo-stress field around the Mediterranean Sea since the Mesozoic from microtectonics: comparaison with the plate tectonic data*. Rocks Mecanics, Supplements 9, 173-192.

MARSICO A., SELLERI G., MASTRONUZZI G., SANSÒ P. & WALSH N. (2003) - *Cryptokarst: the case-study of the Quaternary landforms of southern Apulia (southern Italy).* Acta Carsologica, 32 (2), 147-159.

MARTINIS B. (1962) - *Lineamenti strutturali della parte meridionale della Penisola Salentina.* Geologica Romana, 1, pp. 11-23.

MARTNIS B. (1967) - *Sedimenti calabriani sulle Serre di Calaturo e Castelforte (Penisola salentina).* Rivista Italiana di Paleontologia e Stratigrafia, 73(3), 1023-1038.

MASTRONUZZI G., QUINIF Y., SANSÒ P. & SELLERI G. (2006) - *Middle-Late Pleistocene polycyclic evolution of a geologically stable coastal area (southern Apulia, Italy).* Geomorphology, in press.

PALMENTOLA G. (1987) - *Geological and geomorphological outlines of the Salento leccese region (Southern Italy)*. Atti del Convegno sulle conoscenze geologiche del territorio salentino. Lecce 12 dicembre 1987. Quaderni di Ricerche del Centro Studi Geotecnici e di Ingegneria Lecce, 11, 7-23.

PALMENTOLA G. & VIGNOLA N. (1980) - *Dati di neotettonica sulla penisola salentina. Fogli 204 «Lecce», 213 «Maruggio», 214 «Gallipoli», 215 «Otranto», 223 «Capo Santa Maria di Leuca».* CNR Progetto Finalizzato Geodinamica, pubblicazione 356, 175-202.

PATACCA E. & SCANDONE P. (1989) - *Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab*. The Lithosphere in Italy (Boriani A.M., Bonafede G.B., Piccardo and G.B. Vai Eds.), Atti dei Convegni Lincei, 80, 157-176.

PIERI P., SABATO L. & TROPEANO M. (1996) - *Significato geodinamico dei caratteri deposizionali della Fossa Bradanica nelPleistocene*. Memorie della Società Geologica Italiana, 51, 501-515.

QUINIF Y. (1998) - *Dissipation d'énergie et adaptabilité dans les systèmes karstiques.* Karstologia, 31, 1-11.

RADINA B. (1968) - *Risultati geologici di perforazioni eseguite nei dintorni di Brindisi*. Bollettino Società Naturalisti in Napoli, 77, 207-218.

RICCHETTI G. (1972) - *Osservazioni geologiche e morfologiche preliminari sui depositi quaternari affioranti nel F° 203 «Brindisi».* Bollettino Società Naturalisti in Napoli, 81, 543-546.

SALVATORINI G. (1969) - *Contributo alla conoscenza delle microfaune pleistoceniche della Penisola salentina.* Atti Società Toscana di Scienze Naturali, 76, 232-260.

SELLERI G., SANSÒ P. & WALSH N. (2002) - *The contact karst landscape of Salento peninsula (Apulia, southen Italy)*. Evolution of Karst from prekarst to cessation, 275-281, Postojna.

SHACKLETON N.J. (1995) - *New data on the evolution Pliocene climatic variability*. Paleoclimat and Evolution, with enphasis on human origin (Vrba E.S., Denton G.H., Partridge T.C. & Burkle L.H. Eds.), 242-248, Yale University Press (1996).

SHACKLETON N.J. & OPDYKE N.D. (1973) - *Oxigene isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperature and ice volumes on a 105 year and 106 year scale.* Quaternry Research, 3, 39-55.

TOZZI M. (1993) - *Assetto tettonico dell'avampaese apulo meridionale (Murge meridionali - Salento) sulla base dei dati strutturali.* Geologica Romana, 29, 95-111.

TROPEANO M., SABATO L. & PIERI P. (2002) - *Filling and cannibalization of a foredeep: the Bradanic Truoght*. Sediments Flux to Basins: Causes, Controls, Consequences (S.C. Jonnes & L.E. Frostick Eds.) Geological Society London Special Publication, 191, 55-79.

TROPEANO M., SPALLUTO L., MORETTI M., PIERI P. & SABATO L. (2005) - *Depositi carbonatici infrapleistocenici di tipo foramol in sistemi di scarpata (Salento - Italia meridionale)*. Il Quaternario, 17, 537-546.

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