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MIDDLE-LATE PLEISTOCENE EVOLUTION OF THE ADRIATIC COASTLINE OF SOUTHERN APULIA (ITALY) IN RESPONSE TO RELATIVE SEA-LEVEL CHANGES

ABSTRACT: MASTRONUZZI G., CAPUTO R., DI BUCCI D., FRACASSI U., IURILLI V., MILELLA M., PIGNATELLI C., SANSÒ P. & SELLERI G., *Middle-Late Pleistocene evolution of the Adriatic coastline of Southern Apulia (Italy) in response to relative sea-level changes*. (IT ISSN 0391-9838, 2011).

The Adriatic coastal area stretching from Monopoli to Brindisi in Apulia is characterised by landforms and marine/coastal deposits of Middle-Upper Pleistocene age. An E-W striking fault system, roughly corresponding to the geographic "Soglia Messapica", is also present. This area shows the effects of different phases of coastal evolution. During the Middle Pleistocene, north of the Soglia Messapica, thin coastal deposits accumulated and abrasion surfaces were cut whereas, to the south, marine sediments were deposited. During the last interglacial period, two thin transgressive beach deposits formed along with a dune belt and backdune deposits.

From the geodynamic point of view, facies and elevation of marine and coastal deposits suggest that before 125 ka the region north of the Soglia Messapica was uplifting with a higher rate than the southern one. Afterwards, both areas north and south of the Soglia Messapica showed a similar tectonic behaviour, characterised by stability or, locally, by low subsidence rates. Mesostructural analysis on extensional joints indicates that at least three separate deformational events occurred during the Middle and Late Pleistocene. If matched against the uplift rate changes, this structural evolution may be interpreted as due to the shift toward the SE of the peripheral bulge related to the Ionian slab subduction process and to the set up of a different tectonic event in the Late Pleistocene. In the study area such event is essentially characterised by widespread stability, coupled with the development of joint sets which suggest a doming-like deformation mechanism.

KEY WORDS: Pleistocene, Sea-level changes, Marine terraces, Apulia (Italy).

RIASSUNTO: MASTRONUZZI G., CAPUTO R., DI BUCCI D., FRACASSI U., IURILLI V., MILELLA M., PIGNATELLI C., SANSÒ P. & SELLERI G., *Evoluzione della linea di costa adriatica della Puglia meridionale nel Pleistocene medio-superiore in relazione alle variazioni relative del livello del mare*. (IT ISSN 0391-9838, 2011).

La fascia costiera adriatica fra Monopoli e Brindisi, tra le località di Torre Canne e Torre Mattarelle, è caratterizzata dalla presenza di depositi marini e costieri del Pleistocene, che permettono di riconoscere gli effetti di differenti fasi morfogeniche legate a variazioni relative del livello del mare. L'area è divisa in due regioni differenti da un sistema di faglie ad andamento circa E-O, che individua una discontinuità morfologica in corrispondenza della "Soglia Messapica".

Nel corso del Pleistocene Medio, l'interazione fra il sollevamento regionale e le variazioni del livello del mare consente, nell'area in sollevamento a Nord della Soglia Messapica, il modellamento di una gradinata di superfici di abrasione e/o di pellicolare deposizione, mentre a Sud di tale linea, in relativo abbassamento, si accumularono, intercalati a fasi di emersione, più spessi depositi marini sabbioso-argillosi. Durante l'ultimo periodo interglaciale, su tutta la fascia costiera ebbero luogo due successive fasi trasgressive poco estese che costruirono un sistema di spiaggia-

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cordone dunare-stagno di retroduna ancora ben conservato. L'analisi dei depositi del Pleistocene Medio e Superiore indica che in questo intervallo di tempo l'area a sud della Soglia Messapica è stata caratterizzata da stabilità o, localmente, da relativa blanda subsidenza rispetto all'area a nord in sollevamento. Con il Pleistocene Superiore, forse in relazione alla migrazione del rialzo periferico associato alla subduzione dello slab Ionico, il comportamento è divenuto regionalmente omogeneo a Nord e a Sud della Soglia Messapica, marcato da stabilità o da leggera subsidenza e accompagnato da famiglie di fratture riconducibili a una sorta di deformazione a "duomo" della regione.

TERMINI CHIAVE: Pleistocene, Variazioni del livello del mare, Terrazzi marini, Puglia.

INTRODUCTION

Middle-Upper Quaternary coastal marine landforms and deposits are widespread in Southern Italy and all along the Mediterranean coasts. The best preserved features (marine terraces, notches, sea caves, dune belts, beachrocks) are generally attributed to the Tyrrhenian age (125 ka) or to the Holocene (for a review see: Westaway, 1993; Bordoni & Valensise, 1998; Ferranti & *alii*, 2006; Antonioli & *alii*, 2009 and references therein). If the identification of Holocene deposits is comparatively easy, the Tyrrhenian history, being the last interglacial before the Würm glacial time, does certainly pose larger issues. Also called Riss-Würm interglacial or Eemian or Ipswichian, the Tyrrhenian was proposed between 1911 and 1918, when some authors identified with this term the age of sediments based on the occurrence of *Strombus bubonius* Lamarck, either or not in association with other warm species (Gignoux, 1911a, 1911b; 1913; Issel, 1914; Depéret, 1918). In recent times, the latter terms have been generally referred to the Last Interglacial Time (= LIT), which occurred between about 125 and 80 ka, and correlated with the Oxigen Isotope Stage (OIS) 5 from the curves by Schackleton & Opdyke (1973) and Chappel and Shackleton (1986) or, more recently, to the Marine Isotope Stage (MIS) 5 (e.g.: Schackleton & *alii*, 2003 and references therein). Some characteristic facies of the deposits correlated to the MIS 5 contain a very rich *senegalensis* fauna; in particular, the occurrence of *S. bubonius* seems to mark out the oldest Tyrrhenian deposits, i.e. those referred to the substage 5.5, which occurred about 125±5 ka. Raised coastal sediments and correlated landforms of Middle Pleistocene age are less common and scarcely investigated because of the difficulty to properly date them. Moreover, the generally poor state of preservation of coastal/marine landforms and the lack of characteristic macrofauna assemblages make it difficult to recognise the related sediments. On the contrary, the identification of the last interglacial deposits is relatively easy, and their widespread occurrence in the Mediterranean basin makes them a good regional marker for studying sea-level changes and inferring a geodynamic evolution. In relatively stable regions, MIS 5 marine terraces generally correspond to the lowermost surfaces of a wide flight of marine steps. In Southern Italy, along the coast of the Ionian Sea, MIS 5 deposits with *S. bubonius* (= MIS 5.5) have been recognised in Southern Calabria at about 150 m above present sea level (a.p.s.l.) (Dumas & *alii*, 2005; Dumas and Raffy, 2006), in the Crotone peninsula at about 25 m a.p.s.l. (Palmentola & *alii*, 1990; Zecchin & *alii*, 2004), along the northern coast of Taranto Gulf at about 40 m a.p.s.l. (Boenzi & *alii*, 1985; Zander & *alii*, 2006), and between Taranto and Gallipoli ranging from 12 m a.p.s.l. to the present sea-level (Hearty & Dai Pra, 1992; Belluomini & *alii*, 2002). Finally, geochronological data constrained the occurrence of MIS 5 between Capo Santa Maria di Leuca and Otranto at about 6 m a.p.s.l. (Mastronuzzi & *alii*, 2007). So far in the Mediterranean area, former sea-level stands and, consequently, relative uplift rates have been calculated with great approximation using the elevation of deposits with *senegalensis* fauna. In fact, without valuable geomorphologic or biological evidence, marine terrace surfaces and/or facies analyses allow only a very approximate identification of relative sea-level stand; the miscalculation can exceed 20 m (Ferranti & *alii*, 2006; Caputo, 2007). Deposits marked by s*enegalensis* fauna lack along the entire western and eastern coasts of the Adriatic Sea (Ferranti & *alii*, 2006). This is probably due to the cold marine current pattern affecting the eastern Mediterranean Sea, which prevented the diffusion of these species in the Adriatic Sea (Malatesta, 1985). The occurrence of deposits referred to the last interglacial period was hypothesised by Di Geronimo (1979) and Iannone & Pieri (1982), but it has never been checked against chronological and/or palaeontological data. Recently, the finding of flint remains ascribed to the Mousterian in a colluvial deposit covered by beach/dune cemented sediments, allowed to correlate the latter deposits to a generic MIS 5 (Marsico & *alii*, 2003).

Our study integrates stratigraphic and morphological evidence with palaeontological, archaeological and structural data from the area that overlaps the Murge plateau and the Taranto-Brindisi plain to suggest: a) a relative chronological attribution of marine deposits and landforms that can be recognised along the coast between Bari and Brindisi; b) a reconstruction of the morphological evolution of the Adriatic coast of Apulia during the Middle-Late Pleistocene, in response to climate and sea-level changes as well as to the local and regional geodynamics.

GEOLOGICAL SETTING

1 - REGIONAL GEOLOGY

The study area straddles the south-eastern coast of Apulia, near and around the city of Brindisi. The Apulia region is almost entirely within the Mesozoic Apulia carbonate platform, located on the southwestern margin of the Adriatic block in the central Mediterranean (i.e., Ricchetti & *alii*, 1988; fig. 1). It represents the foreland domain, elongated from NW to SE, shared by the Apennines chain to the west and the Dinarides chain to the east. The geodynamic setting of the region is characterised by the ongoing subduction of the Ionian slab beneath the Calabrian Arc,

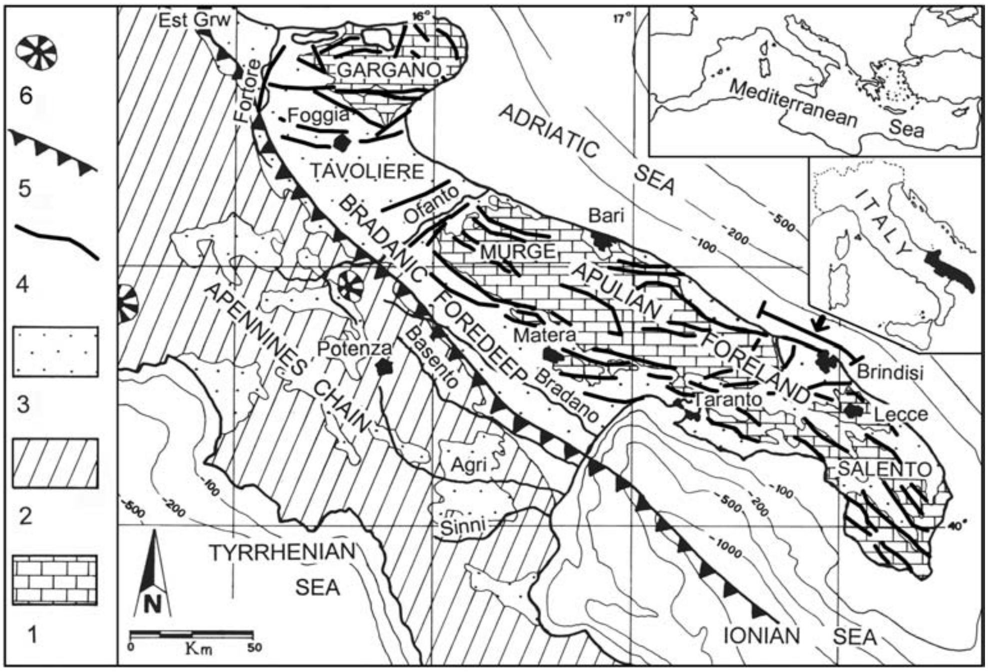


FIG. 1 - Location and geodynamic sketch of studied area. Legend: 1 - Apulian foreland units; 2 - Apennines chain units; 3 - Bradanic foredeep and Plio-Pleistocene units; 4 - main faults of the Apulian regions; 5 - compressional front of the Apennines; 6 - Mt. Vulture volcano.

as outlined by seismicity distribution (Caputo & *alii*, 1970; Castello & *alii*, 2005). The associated wedge front of the Apennines-Maghrebian chain is active in the Ionian Sea, where it deforms the seafloor (Doglioni & *alii*, 1999). In the Taranto Gulf, the Calabrian units are tectonically stacked onto the Apennines wedge (Bigi & *alii*, 1990). Tilted Upper Pleistocene marine deposits suggest a possible activity associated with this wedge also onshore (Vezzani, 1967; Boenzi & *alii*, 1976; Bianca & Caputo, 2003; Caputo & *alii*, 2010). This activity should taper to zero moving towards the NW, where according to Patacca & Scandone (2004) the migration of the Southern Apennines toward the Adriatic foreland ceased at the beginning of the Middle Pleistocene (~650 ka). Moreover, the region seems to be also affected by the effects of the SW-direct migration of the Dinarides, Albanides and northern Hellenides complex. Along the northeastern side of the Adriatic Sea, the compressional regime presently affecting these fold-and-thrust belts is well depicted by the relevant seismicity and related focal mechanisms, joined with a detectable sudsidence of the Albanian coasts and an evident uplift of the Hellenic ones (see: Pirazzoli & *alii*, 1994; Harvard CMT Project, 2006). Finally, the current geodynamic frame of the Adriatic foreland is still dominated by the NW-SE Eurasia-Nubia convergence (De Mets & *alii*, 1994; Sella & *alii*, 2002; McClusky & *alii*, 2003; Serpelloni & *alii*, 2007). This convergence has been interpreted as responsible for the recent and active deformation of other parts of the Adriatic foreland (Caputo, 1996; Di Bucci & Mazzoli, 2003; Caputo & *alii*, 2003; 2010; Valensise & *alii*, 2004; Di Bucci & *alii*, 2006; 2010; Ridente & *alii*, 2008). The Apulia region is segmented by several parallel NNW-SSE trending normal faults (fig. 1). Secondary faults, striking oblique or perpendicular to the main normal faults, cut Apulia into three main disengaged structural blocks characterised by different uplift rates during the Pleistocene: the Gargano promontory, the Murge plateau and the Salento peninsula. These blocks are separated by lowlands which are affected by comparatively lower uplift rates (C.N.R., 1987; Tozzi, 1993), namely: the Tavoliere alluvial plain, the Ofanto graben and the Taranto-Brindisi plain. The study area overlaps the Canale Reale, the river that separates the Murge plateau from the Taranto-Brindisi plain (fig. 2).

The ca. 6 km thick Mesozoic limestone is overlain by thin (up to 70 m), discontinuous marine deposits of Plio-Pleistocene age, belonging to the *Calcarenite di Gravina* and the etheropic *Argille subappennine* (Ciaranfi & *alii*, 1988). These units are covered by Middle-Upper Pleistocene bioclastic beach and dune calcarenite deposits; they crop out as stepped terraces stretching from about 400 m to a few metres above the mean sea-level (e.g., Mastronuzzi & Sansò, 2003). The oldest deposits contain volcanoclastic products from Mt. Vulture. This volcano, located about 200 km off the study area, was active from the early Middle Pleistocene (*Fara d'Olivo ignimbrites*, aged 730 ±20 ka) to the latest Middle Pleistocene, about 132 ka (Ciccacci & *alii*, 1999). The volcanic cone is drained by the Ofanto river and its tributaries, which carry the volcanic material to the Adriatic shoreline north of the study area. The resulting clastic sediments are transported souteastwards along the coast line, down drift (Mastronuzzi & Sansò, 1993). The younger marine terrace deposits are frequently characterised by the presence of a *senegalensis* faunal assemblage that, togheter with U/Th age determinations performed on *Cladocora caespitosa*, allows to ascribe their deposition to he MIS 5 (sensu Shackleton & Opdyke, 1973); (Mastronuzzi & Sansò, 2003 and references therein).

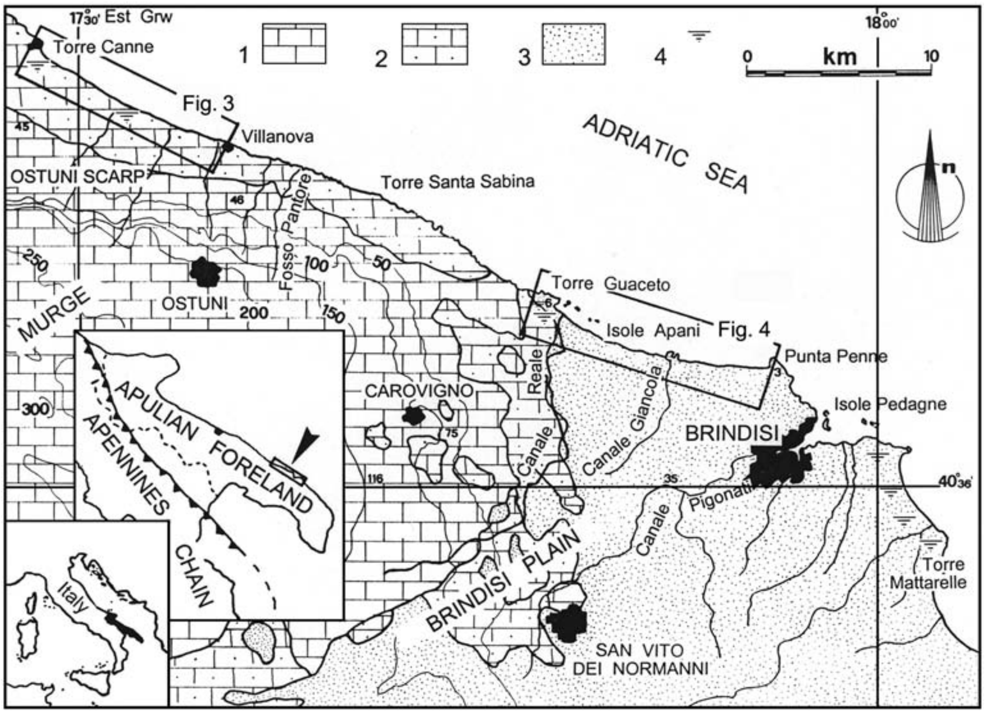


FIG. 2 - Location of the localities mentioned in the text. Legend: 1 - Mesozoic limestone; 2 - Plio-Pleistocene calcarenites; 3 - Middle-Upper Pleistocene Deposits; 4 - swamp areas.

2 - NEOTECTONICS

Throughout the Middle and Late Pleistocene, southern Apulia was affected by a mild brittle deformation with rare faults characterised by small displacement and widespread extensional joints, frequently organised in sets (Caputo & *alii*, 2008; Di Bucci & *alii*, 2009; 2011). In general, SW-NE to SSW-NNE extension prevails all over southern Apulia, recorded in Middle-Late Pleistocene deposits surveyed both along the Ionian and Adriatic sides. Along the Adriatic side, the WNW-ESE extension seems to prevail from Monopoli to Brindisi (Di Bucci & *alii*, 2009). Moreover, detailed analyses of the marine terraces facing the Taranto Gulf suggest that during the Late Pleistocene, possibly up to the Holocene, the activity of the Apennines thrusts continued (Bianca & Caputo, 2003; Caputo & *alii*, 2007; 2010). According to Doglioni & *alii* (1994; 1996), the uplift of the Apulia region began during Middle Pleistocene.

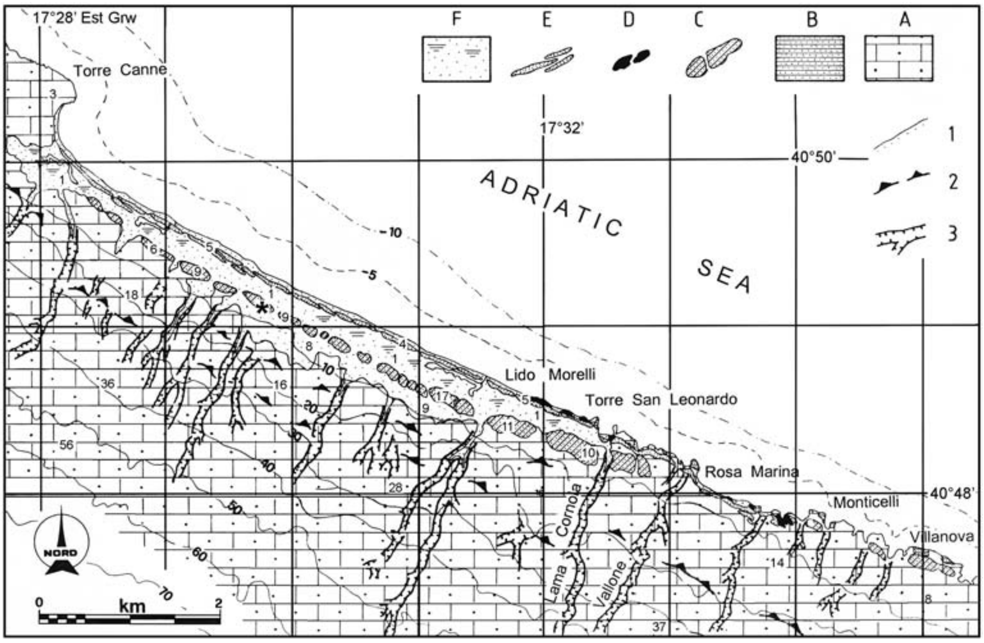
Recent overviews of all the deposits/landforms ascribed to the MIS 5.5 allow to further detail the southern Apulia tectonic behaviour. Uplift rates decrease from more than 1 mm/a to ca. 0.3 mm/a from southwest to northeast along the Ionian coast of the Taranto Gulf (Caputo & *alii*, 2004; 2010; Mastronuzzi & Sansò, 2003) and from north to south on the Ionian side of Apulia, and from 0.25 to 0.14 mm/a in the area of Taranto. These values taper to zero toward the southernmost part of the Salento peninsula, where the markers of MIS 5.5 are about at the eustatic level (Mastronuzzi & *alii*, 2007). Ascertaining the tectonic behaviour along the Adriatic side proves to be less straightforward. Due to the lack of geochronological and/or palaeontological absolute constraints, only the morphological evidence can be used as indicator of local vertical movements (Mastronuzzi & Sansò, 2002a; 2003). Finally, marine deposits related to the MIS 5 and cropping out north of Bari and south of Brindisi host seismites probably related to nearby strong earthquakes occurred during the Late Pleistocene (Moretti & Tropeano, 1996; Tropeano & *alii*, 1997; Moretti, 2000).

METHODS

We performed a geological and morphological field survey all along the coastal area stretching between Torre Canne and Torre Mattarelle; it has been extended inland up to the Ostuni composite scarp (fig. 1; 2). Geomorphological sketches have been produced for the most significative areas (fig. 3; 4). Data deriving from stratigraphic, lithological and paleontological analyses have been correlated with geochronological ones (fig. 5). When possible, in consideration of the mineralogical features, optically stimulated luminescence (OSL) age determinations have been performed on calcarenites sampled in the marine and aeolian facies (tab. 1). Moreover, 14C age determinations have been performed on terrestrial gastropods sampled in the aeolian sediments (tab. 2).

We carried out a statistical analysis on extensional joints by applying an inversion technique pro-posed by Caputo & Caputo (1989) in order to infer the orientation of the principal stress axes and their ratio. We measured the joint orientations and their opening vectors (Caputo & *alii*, 2008; Di Bucci & *alii*, 2009); observations have been made by attempting a 3D vision of the outcrops.

FIG. 3 - Geomorphological sketch of the coastal area between Torre Canne and Villanova. Legend: A) *Calcarenite di Gravina*; B) MIS 5 beach; C) MIS 5 aeolianites; D) Mid-Holocene aeolianites; E) Roman Age aeolianites; F) backdune deposits; 1) sandy beaches; 2) relict cliffs; 3) sapping valleys.



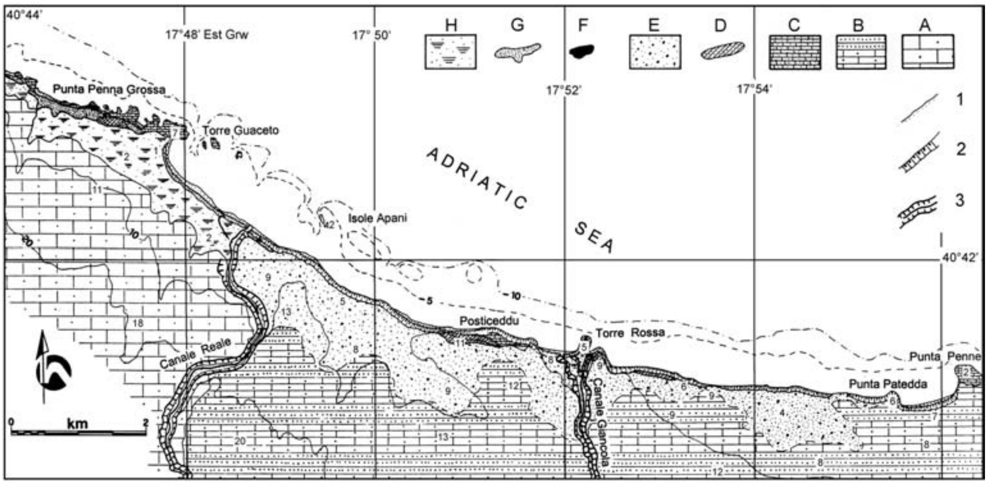


FIG. 4 - Geomorphological sketch of the coastal zone between Torre Guaceto and Punta Penne. Legend: A) *Calcarenite di Gravina*; B) Middle Pleistocene yellow sands and sandstones; C) MIS 5 beach; D) MIS 5 aeolianites; E) MIS 5 continental lagoon red sands; F) Mid-Holocene aeolianites; G) Roman age aeolianites; H) backdune deposits and lagoons; 1) sandy beaches; 2) cliffs; 3) river valleys.

TABLE 1 - OSL ages (±1σ) of samples deriving from the pre-Holocene costal deposits of the Adriatic coast of Puglia performed by Dr. PhD B. Mauz into the Luminescence Dating Laboratory, University of Bonn (Germany). Water content is the measured field moisture normalised to the dry mass and corrected for fluctuation of water content; U-, Th-, and K-concentrations are determined by γ-spectrometry and used to calculate the total dose rate; **.D$_{cosm}$** is the cosmic dose rate determined from the mean burial depth of the sample; **.D$_{effective}$** is the total dose rate corrected for water absorption; OSL- Recuperated OSL-signal is given in % of the natural OSL signal, recycling ratio is the ratio of the first regenerated dose and the repeated first regenerated dose at the end of the SAR protocol; **De(t)** indicates the stimulation time range (s), where De is constant (1σ); IR sensitivity indicates a feldspar component based on the IR OSL signal. Ages are given with 1σ error limits. n.d. = not determinable (Mastronuzzi & Sansò, 2003)

Sample	Deposit	Locality	Mat.	Water Content	U (μg g^{-1})	Th (μg g^{-1})	K (wt %)	.D$_{cosm}$ (Gy ka^{-1})	.D$_{effective}$ (Gy ka^{-1})	D$_e$ (Gy)	De (t)(s)	Recuperation	Recycling Ratio	Dose Recovery	IR sensivity	Age ka (±1σ)	Reference
BN 101	Aeolian	Lido Morelli	Quartz	1.25±0.20	3.02±0.07	2.59±0.03	0.170±0.009	0.181±0.009	1.09±0.05	–	–	0.04±0.02	1.05±0.02	–	–	n.d.	Mastronuzzi & Sansò, 2003
BN 102	Beach-foreshore	Monticelli	Quartz	1.10±0.10	–	–	–	0.171±0.009	–	≥204	–	6.8±4.2	–	–	0.2±0.1	>75	Mastronuzzi & Sansò, 2003
BN 103	Beach-shoreface	Apani	Quartz	1.15±0.15	1.27±0.03	11.39±0.36	1.69±0.05	0.161±0.008	2.56±0.51	>200	–	–	–	0.806±0.02	0.09±0.01	n.d.	Mastronuzzi & Sansò, 2003
BN 106	Beach-shoreface	Torre Rossa	Quartz	1.06±0.06	0.83±0.03	1.80±0.11	0.56±0.03	0.15±0.00	1.32±0.4	–	–					n.d.	Mastronuzzi & Sansò, 2003
BN 113	Aeolian	Il Pilone	Quartz	1.16±0.15	1.73±0.05	2.48±0.89	0.50±0.00	0.19±0.01	1.18±0.06	6.09±0.16	0–4	0.03±0.01	–	–	0.06±0.01	5.35±0.29	Mastronuzzi & Sansò, 2003

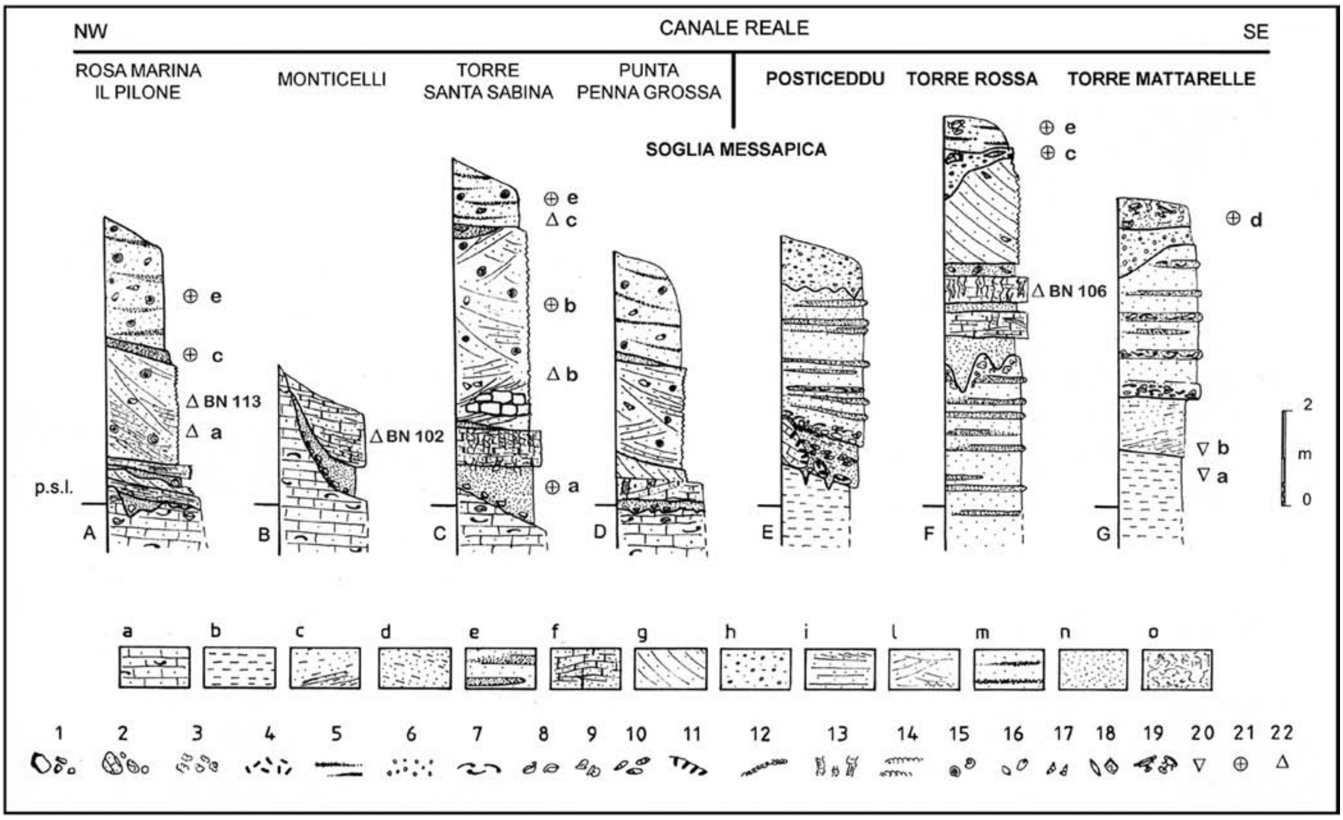


FIG. 5 - Lithological, sedimentological, paleontological, archaeological and chronological features of surveyed geological sections. Legend: a) cemented calcarenite; b) blue sandy clays; c) green clayey sands; d) pale green sandy clay; e) yellow sands and sandstones; f) well cemented calcarenites; g) well cemented eolianites; h) continental lagoon red sands; i) cemented calcarenites; l) cemented eolianites; m) loose eolianites; n) red colluvium; o) present soil; 1) breccia; 2) conglomerate; 3) calcrete nodules; 4) volcanic heavy minerals; 5) brown soil; 6) manganese nodules; 7) bivalves; 8) brachiopods; 9) pectinds; 10) *Neopycnodonte* sp.; 11) *Lithophaga* borings; 12) algal encrustations; 13) bioturbations; 14) echinoid traces; 15) *Helix* sp.; 16) *Pomatia* sp.; 17) *Rumina* sp.; 18) pre-classic remains; 19) Greek-Roman remains; 20) nannoplancton data: a - Sicilian, b - Sicilian; 21) archaeological data: a - Upper Palaeolithic and Neolithic age; b - ancient Neolithic wall; c - Neolithic; d - remains of Bronze, Iron and Roman Age; e - remains of Greek-Roman Age; 22) geochronological data: a - 6900±90 years BP, b - 6084±52 years BP, c - 2110±90 years BP; d - 5291±120 years BP; e - BN 113; f - BN 102; g - BN 106 (for these last chronological and archaeological data see Mastronuzzi & Sansò, 2002b; 2003 and references therein).

TABLE 2 - Radiocarbon age determinations on terrestrial gastropods sampled on cemented dune sediments. Analyses were performed in the Laboratorio di Geochimica Isotopica, University of Trieste (Italy) (Mastronuzzi & Sansò, 2003)

Sample	**Deposit**	**Locality**	**Material**	**δ13CPDB (‰)**	**δ18° (‰)**	**Age (a)**	**Lab.**	**Reference**
P15	Aeolian	Torre Rossa	*Pomatia* sp.	-3,98	-1,58	32.000±1125	A	Mastronuzzi & *alii*, 2001
P16	Aeolian	Lido Morelli	*Pomatia* sp.	-7,55	-4,42	21.750±365	A	Mastronuzzi & *alii*, 2001

MORPHOLOGICAL AND STRATIGRAPHIC DATA

The coastal region from Torre Canne to Torre Mattarelle can be divided into two areas characterised by distinct geological and morphological features; their boundary can be identified along the Canale Reale river, which approximately flows along an E-W striking fault system (fig. 1).

1 - MORPHOLOGY

The landscape to the north of the Canale Reale river is characterised by the Ostuni composite scarp, which separates the coastal area from the Murge karstic plateau. Almost at the top, at about 250 m a.p.s.l., small outcrops of aeolianites are preserved. The height of the Ostuni scarp gradually diminishes towards SE, and the scarp finally disappeares near Torre Guaceto. Seawards, gently sloping surfaces are shaped on both the Mesozoic basement and the *Calcarenite di Gravina.* Locally, discontinuous low steps drawn a staircase geometry stretching from about 150 m a.p.s.l. to the present sea-level (fig. 3). The coastal plain is cut by a drainage network formed by small sapping valleys, locally named *lame* (Mastronuzzi & Sansò, 2002a).

On the contrary, the landscape to the south of the Canale Reale is characterised by a quasi-continuous surface shaped on different lithological units and extending from an elevation of ca. 150 m to the sea-level. This landscape has been slightly dissected by a poorly developed drainage network. The coast between Torre Guaceto and

Torre Mattarelle is generally characterised by cliffs cut into clays and sands and thus rapidly retreating (figs. 2 and 4). The continuous line of cliffed coasts is interrupted only in the vicinity of Brindisi, where a deep *ria* located at the mouth of the Pigonati river and some swamps can be found (fig. 2).

2 - LOWER-MIDDLE PLEISTOCENE STRATIGRAPHY

Along the coastal plain to the NW of the Soglia Messapica, the *Calcarenite di Gravina* crops out from Torre Canne to Torre Guaceto (fig. 2); only along the coastline, the lowest surface, at 2-3 m a.p.s.l., is covered by beach sediments (fig. 3; fig. 5 A-D) (Mastronuzzi & Sansò, 2003).

The area to the SE of the Soglia Messapica stretches from Torre Guaceto to Torre Mattarelle (fig. 4) and is characterised by a more complex stratigraphic setting. The most complete succession was found along active cliffs (fig. 5 E-G). The oldest deposits are pale-green sandy clays, overlain by pale-green clayey sands, rich in *Neopycnodonte* sp. The transgressive contact between these two lithologies is marked by blocks characterised by numerous bivalve borings. Yellow sands and sandstones up to 10 m-thick follow upwards transgressively. They are characterised by a cold water fauna, dominated by *Hyalinea balthica* (Schroeder), *Arctica islandica* (L.) and *Turritella incrassata* (Sowerby) (Di Geronimo, 1969). The yellow sands and sandstones also display layers mainly formed by bivalve shells (*lumachella*) and numerous layers rich in well-rounded heavy minerals (pyroxenes and garnets) coming from Mt. Vulture volcano. Palaeontological and mineralogical data constrain the deposition of the yellow sands and sandstones after the inception of Mt. Vulture activity; moreover, the cold water fauna suggests a deposition which predates the MIS 5. Therefore, these deposits can be referred to a generic Middle Pleistocene. This unit can be recognised along the coast south of Torre Guaceto and the Canale Reale and it crops out extensively landwards. At Torre Mattarelle (fig. 5 G), these sands transgressively cover two sandy clay units ascribed to the Lower-Middle Pleistocene on the basis of the nannoplankton content marked by the presence of *Gephyrocapsa* SP3. Finally, recent studies carried out on a silty-clay succession, exposed along the Torre San Gennaro cliff, returned a Lower-Middle Pleistocene age (Coppa & *alii*, 2001).

3 - UPPER PLEISTOCENE DEPOSITS STRATIGRAPHY

Well-cemented, beach/dune deposits crop out all along the coastline of the studied area to the NW of the Soglia Messapica (fig. 3). They cover an abrasion platform shaped on the Calcarenite di Gravina, placed up to 3 m a.p.s.l; the contact is often marked by a red palaeosoil up to 1 m-thick (fig. 6 A, B). This unit is intensely bioturbated yet characterised by the lack of marine fossil remains. Along several tracts, beach deposits are bordered landwards by a small cliff 2-5 m-high that approximately marks a relict coastline, although it does not indicate the exact elevation of the former sea-level.

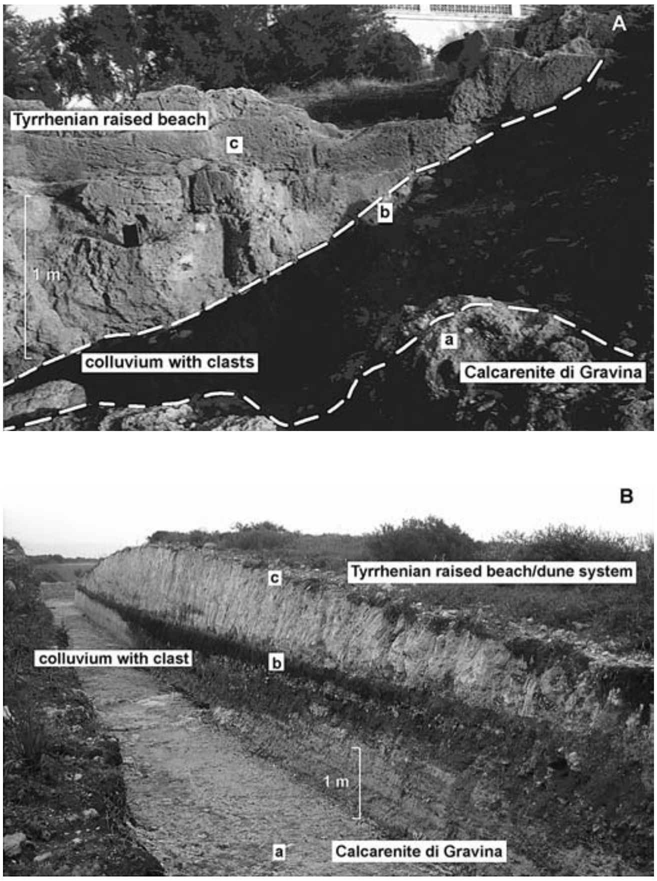


FIG. 6 - A - Monticelli locality; the contact between the MIS 5 beach deposit (c) and the *Calcareniti di Gravina* (a) is marked by a red colluvium with clasts (b) (see fig. 5); B - The dune/beach sediment (d1/d2) near Lido Morelli locality (marked by * in fig. 3).

To the SE of the Soglia Messapica, Upper Pleistocene deposits are at the top of Middle Pleistocene yellow sands and sandstones (fig. 5 F; G); both beach deposits and Middle-Late Pleistocene succession are strongly eroded by waves that cut a 5-8 m-high cliff. The beach deposits, whose base is at about 3-4 m a.p.s.l., are often covered by a well developed and typical aeolian deposit (fig. 7 A; B). In the area of Brindisi-Punta Penne, the beach deposits are up to 2 m a.p.s.l., and are characterised by high-angle lamination (fig. 8); they have been ascribed to a beach barrier of generic Upper Pleistocene age (Loiacono & *alii*, 2002).

The aeolian deposit forms a dune belt that reaches a maximum elevation of about 17 m a.p.s.l. and borders landwards the raised beach. At about 200 m landward from Torre Canne bay, the dune belt runs NW-SE, i.e. parallel to the present coast line (fig. 3). In the central part of this area, the dune belt can be found at 17 m a.p.s.l., whereas it shows the maximum development at the south-eastern side of the palaeobeach. These circumstances suggest that, when the dune belt formed, dominant winds blew from the N or NW as at present. The dune belt is presently cut by a number of little sapping valleys whose last shaping phases were ascribed to the MIS 2 (Mastro-

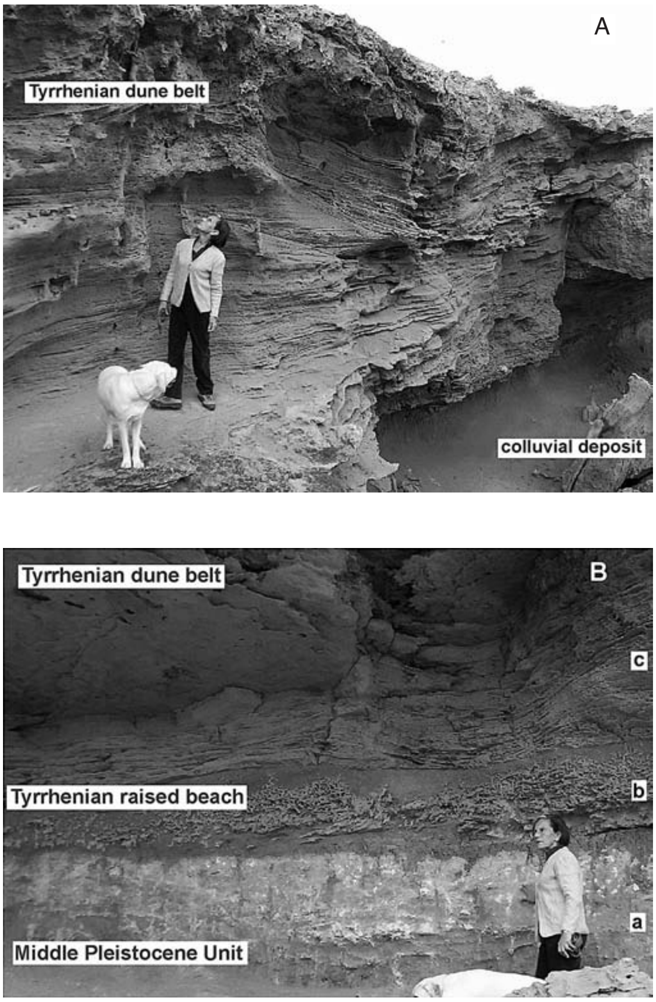


FIG. 7 - Torre Rossa locality. (A) A general view of the MIS 5 aeolian deposits; (B) the entire sequence repre-sented by (a) Middle Pleistocene yellow sands and sandstones, (b) Tyrrhenian (MIS 5) raised beach (d1) and (c) Tyrrhenian (MIS 5) dune belt (d3) and interbedded colluvial deposits; the dune d2 connected to the beach d1 out-crops inland.

nuzzi & *alii*, 2002; Mastronuzzi & Sansò, 2002a). The aeolianite consists of a well-cemented, light-brown, fine, bioclastic calcarenite with high-angle cross-lamination (fig. 7 A). It contains small amounts of quartz crystals and other silicates, and it is rich in pyroxenes and garnets coming from the Mt. Vulture volcano. Absolute age cannot be ascertained by means of U/Th dating methods, because no corals or marine shells have been found in this deposit; however, the numerous OSL analyses carried out on these clacarenites returned a generic Late Pleistocene age (tab. 1) (Mastronuzzi & Sansò, 2003). Dunes contain remains of rare terrestrial Gastropods; a *Helix* sp. sample, collected near Lido Morelli, and a *Pomatia* sp. sample, collected in the Torre Rossa locality (fig. 5 F), yielded ^{14}C non calibrated ages of 21,750 ±365 and 32,110 ±1,125 years BP (tab. 2).

In many cases, dune and/or beach calcarenites show a dark red colluvial deposit at their bottom; moreover, red continental clayey sands often occur behind the dune belt.

FIG. 8 - Joints on calcarenites (Punta Penne, near Brindisi).

These up to 4 m-thick deposits are generally massive and rich in pedogenic pisolites and manganese coatings. They partly fill the backdune depression and are easily recognisable where the present coastline has overcame the previous one and exposed them in cross-section, for instance between Torre Guaceto and Posticeddu (fig. 4). This deposit yielded the only valuable chronological constraint found. In Santa Sabina locality, it hosts a man-splinted flint, and human frequentation is well-documented in this area since the Middle Palaeolithic; this indicates an age younger than Middle Palaeolithic for the overlying calcarenite, which can be therefore correlated to a generic MIS 5 (Marsico & *alii*, 2003).

4 - STRUCTURAL DATA

In general, the extension joints form sets of nearly parallel planes (fig. 8). Locally a unique joint set was identified, but the occurrence of two well developed, roughly orthogonal sets is more common. In few but crucial cases, more than two joint sets exist. Following the basic concepts proposed by Hancock (1985) to determine the relative timing of fractures, we spent particular care in the field to observe the occurrence of mutual or systematic abutting relationships between joints belonging to different sets. It is assumed that two orthogonal joint sets within the same site are genetically related to a unique remote causative stress field if mutual abutting relationships, which document geologically coeval formation, are found (Caputo, 1995). Accordingly, in case two orthogonal joint sets reciprocally abut, they have been analysed as a unique system; otherwise, they have been separated before performing the numerical inversions.

Based on the mesostructural analysis of the Quaternary deposits and on the numerical inversions of the elaborated datasets, we firstly observe that all the "local" stress tensors calculated for each site are characterized by a vertical maximum principal stress axis (σ1), therefore documenting the occurrence of an extensional tectonic regime (*sensu* Anderson, 1942) throughout the entire area. Secondly, the two horizontal principal stress axes (σ2 and σ3), although variably oriented in the different sites, show some recurrent directions. Thirdly, in some sites we observed two distinct joint systems, which we interpreted as the result of different stress fields occurred in subsequent periods.

Our results allowed us to reconstruct the Middle and Late Quaternary tectonic stratigraphy of the southern Adriatic foreland of Italy (Caputo & *alii*, 2008). By integrating such analysis of the extension joints with geological and litho-stratigraphic information, we were able to organise our dataset in three groups of data, which show the occurrence of at least three separate deformational events during the Middle and Late Quaternary in the study area (fig. 9).

The first subset of data includes six sites with horizontal principal stress axes ($\sigma 2$ and $\sigma 3$) roughly trending N-S and E-W (fig. 9a). These sites are distributed all over the investigated area, therefore suggesting the regional significance of this deformational event. In many cases, the E-W joint set dominates, while locally the N-S prevails. In all cases, extension is almost uniaxial, as documented by the ratio R that varies in the 0.64-0.99 interval, with prevailing values near the upper bound. Taking into account the age of the hosting deposits, the age of the second subset of data (see below in this same section) and the abutting relationships with the other joints analysed, the deformational event represented by the first subset of data is constrained to the early and middle part of the Middle Pleistocene.

The second subset of data has been observed in ten sites (fig. 9b). The estimated stress tensors are characterized by an almost uniaxial tension, represented by an ellipsoid of revolution around the horizontal $\sigma 3$ axis. This is the reason why the orientation of the $\sigma 1$ and $\sigma 2$ axes could be locally meaningless and in two cases they are even interchanged. The orientation of the least principal stress ranges between N22° and N62°, with a mean value of ~N43°. The stress ratio R is high, ranging between 0.85 and 0.99. Based on the age of the hosting rocks and on the analysis of the sites characterized by more than one joint system, a late Middle Pleistocene age can be reasonably assigned to this deformational event.

The third subset of data includes twelve sites covering the entire investigated area, from north to south and from the Adriatic to the Ionian coasts (fig. 9c). The common feature which characterizes the stress tensors calculated for this subset is a low R ratio, with values that never exceed 0.47 and are frequently lower than 0.3. Such values correspond to an ellipsoid that tends to be of revolution around the s1 vertical axis; the $\sigma 2$ and $\sigma 3$ axes are comparable, thus indicating a sort of horizontal "radial" extension. Even though the remote $\sigma 2$ and $\sigma 3$ axes were quite similar in magnitude, at least as an average in space and time, due to the stress swap mechanism (Caputo, 1995) the related joints commonly cluster in two roughly orthogonal sets statistically equivalent. It is worth mentioning that all the youngest investigated sites, consisting of Upper Pleistocene calcarenites, are included in this subset. Sites characterized by older Quaternary deposits show systematic abutting relationships which demonstrate that these joint sets are the youngest of the entire dataset considered. Accordingly, this is the most recent deformational event recognised; it is not older than the Late Pleistocene and possibly reflects the active stress field still pervading (at least) the shallower sectors of the entire study area.

DISCUSSION

1 - CHRONOLOGICAL CONSTRAINTS

The entire data set and their integrated analyses allowed the characterization of both marine and terraced beach deposits identifying some marine units (fig. 10) heteropic or overlayed on the local basement represented by the *Calcarenite di Gravina* (a in fig. 10).

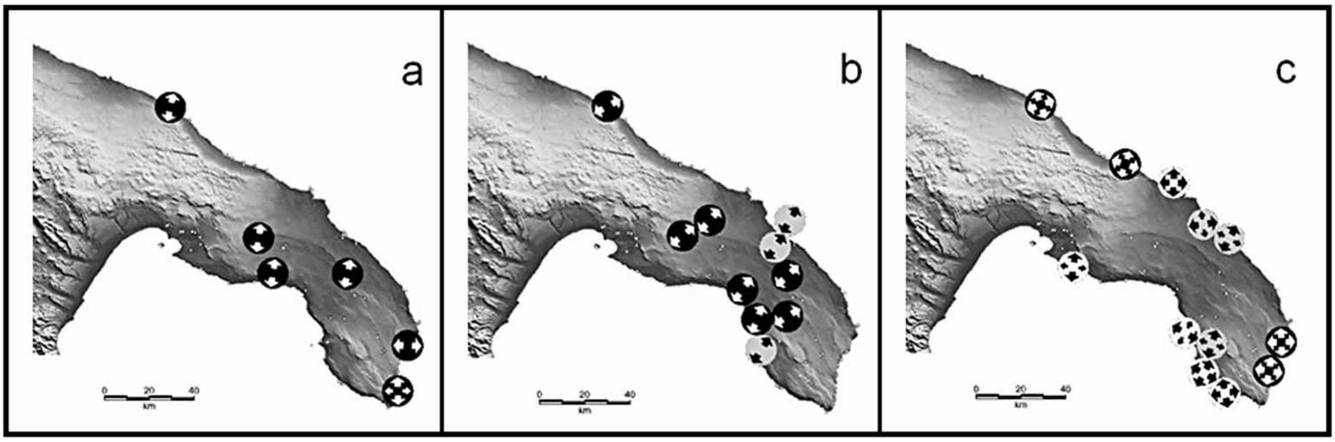


FIG. 9 - Deformational events recognized (from Caputo & *alii*, 2008). The arrows in the circles show the direction of horizontal extension, while the gray-scale of the circles refers to the age of the youngest deposit involved at the site (black = late Lower Pleistocene; gray = Middle, late Middle and Middle-Upper Pleistocene; white = Upper Pleistocene). *a*) First subset of data, that has been associated with the oldest deformational event, ascribed to the early and middle part of the Middle Pleistocene; *b*) Second subset of data, that has been associated with the penultimate deformational event, ascribed to the late Middle Pleistocene; *c*) Third subset of data, that has been associated with the most recent deformational event, not older than the Late Pleistocene.

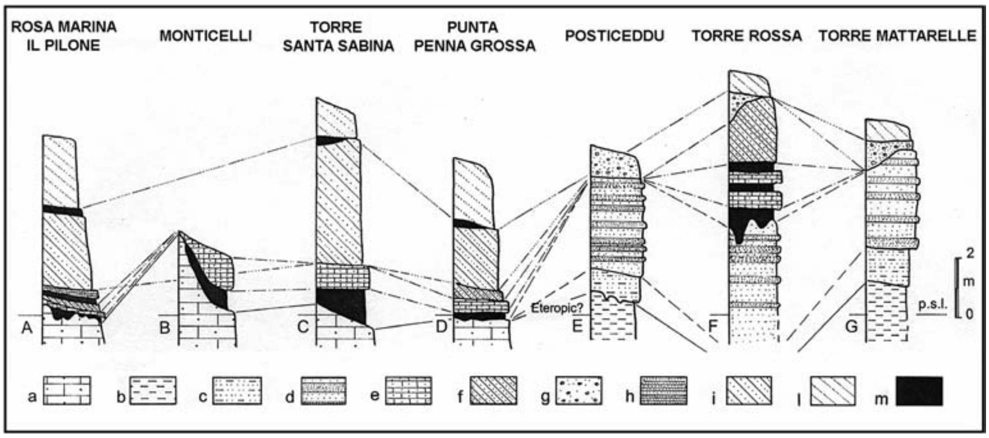


FIG. 10 - Synoptic sketch of the relationship between stratigraphical units (letters do not correspond to those of fig. 5). Legend: a) *Calcarenite di Gravina* (Upper Pliocene-Lower Pleistocene); b) *Argille subappennine?* (Sicilian); c) pale green sands (Lower Pleistocene); d) yellow sands and sandstones (Middle Pleistocene); e) beach calcarenite (Upper Pleistocene-MIS 5); f) aeolianites (Upper Pleistocene-MIS 5); g) continental lagoon red sands (Upper Pleistocene-MIS 5); h) beach calcarenite (Mid-Holocene); i) aeolianites (Mid-Holocene); l) aeolianites (Greek-Roman Age); m) colluvium.

Unit a - the lowermost and oldest unit is formed by pale green sandy clays and blue sandy clays (b in fig. 10); the nannoplankton content suggests a Sicilian (latest Early Pleistocene) age. These clays are at the same elevation of the *Calcarenite di Gravina* but their relationships are still unknow; they could be considered as corresponding to the *Argille subappennine* (blue clays), which crop out all along the Ionian side of Apulia. An alternative interpretation could see them as resulting from the circa-coeval deposition of a terrigenous deposit in a separated and limited basin.

Unit b - transgressive on the **Unit a**, pale green clayey sands occur (c in fig. 10); they are attributed to the Middle-Early Pleistocene, according to nannoplankton and stratigraphical data.

Unit c - also this unit is transgressive. It is formed by yellow sands and sandstones (d in fig. 10), which can be referred to the Middle Pleistocene due to the occurrence of **(i)** heavy minerals deriving from the Mt. Vulture volcano, and **(ii)** cold water fauna not compatible with the MIS 5.

Units d1/d2-d3/d4 - the formation of the beach deposits (**d1** = e in fig. 10) and of the first and oldest dune belt (**d2** = f in fig. 10) are genetically linked. The second dune belt (**d3** = f in fig. 10) seems overlain the beach (**d2**); this could indicate a second transgressive phase. Unfortunately, no data are available to precisely date these two transgressive phases, since they do not contain significant fossil remains (i.e., tropical fauna). The beach deposits (**d1**) and dune belts (**d2-d3**) can be generically attribute to the LIT. Such age attribution is based: **i** - on the occurrence of sapping valleys that cut the above units, valleys whose last phase of shaping has been attributed to the Last Glacial Maximum (LGM) (Mastronuzzi & *alii*, 2002); **ii** - on the presence of archaeological remains in the red colluvial soil below the beach/dune sediments (Marsico & *alii*, 2003). Moreover, the backdune sediments (**d4** = g in fig. 10) located landward of the oldest dune belt show deep weathering, possibly resulting from the wet-warm climatic conditions that occurred during the last interglacial period and also responsible for widespread washing of the higher surfaces. Dune belt deposits (**d2-d3**) yielded a ^{14}C age ranging from 33,000 to about 23,000 years BP that we consider really unlike, not only because these values lie at the limit of the dating method, but also because they lack a morphological confirmation. On the one hand, the available absolute age indicates that this aeolian dune belt should have formed during the last phases of the isotopic stage 3 up to stage 2, when the sea level was much lower, at about –50 m b.p.s.l. (e.g., see Antonioli & *alii*, 2004; Lambeck & *alii*, 2004; Ferranti & *alii*, 2006; Caputo, 2007). On the other hand, the most reliable OSL age determinations (tab. 2) seem to indicate an older age, i.e. 75 ka (Mastronuzzi & Sansò, 2003). Considering: **ì**) the occurrence of colluvial deposits with flint remains at the base of these dune deposits, and **ìi**) that the age and elevation of these coastal deposits agree with the most recent eustatic curves (see Ferranti & *alii*, 2006; Caputo, 2007 and references therein) and with other data collected along the eastern side of southernmost Apulia (Mastronuzzi & *alii*, 2007), the correlation with a generic MIS 5 should be preferred. The Pleistocene units are finally overlain by more recent Holocene deposits (h, i, l in fig. 10) (see Mastronuzzi & *alii*, 2001; Mastronuzzi & Sansò, 2002b).

2 - MORPHOLOGICAL EVOLUTION

From the analysis of Pleistocene deposits and landforms it was possible to recognise some major distinct periods of morphogenic, continental and/or marine, evolution, occurred during the Pleistocene and Holocene.

During the Middle Pleistocene, after the deposition of *Calcarenite di Gravina* and younger clayey units, the synergic action of a persistent (possibly constant) uplift and of relative sea-level high-stands produced a number of abrasional/depositional platforms arranged in staircase geometry NW of Torre Guaceto. In contrast, the southeastern area was marked by relative slight subsidence/vertical stability, and deposition of thick yellow sands and sandstones occurred (fig. 11). Since the Middle Pleistocene, but mainly during the Late Pleistocene up to the Early Holocene, a large part of the coastal area at the base of the Murgia escarpment was exposed to rhexistatic continental dynamics. It was conditioned by the alternance of warm umid/tropical and cold dry/continental climates, the latter charac-

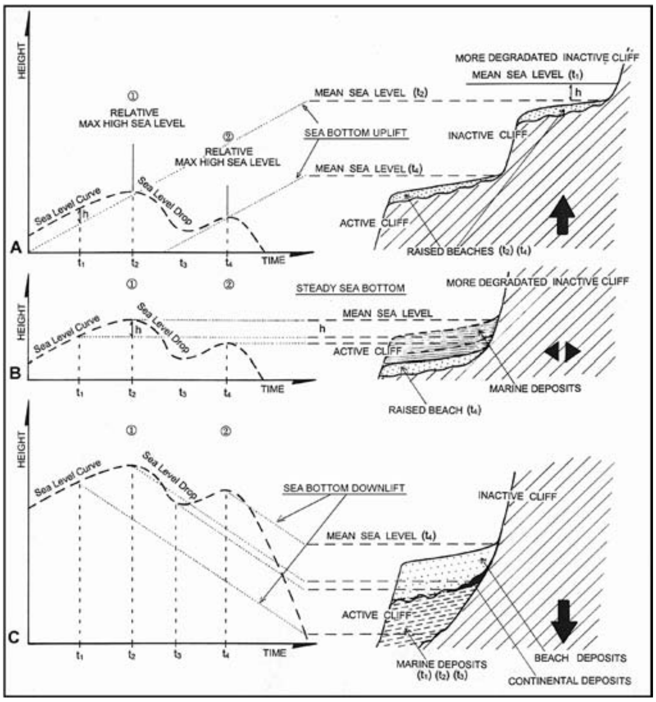


FIG. 11 - Sketch showing relation between tectonics, sea-level curve, morphologenetic phases and sedimentation: A) effects of sea-level change on uplifting basement (North of Canale Reale); B) effects of sea-level changes on steady basement; C) effects of sea-level changes on basement in relative subsidence (South of Canale Reale).

terised by steppes with *Artemisia* (e.g., Watts, 1985; Prentice & *alii*, 1992; Rossignol-Strick & *alii*, 1992; Rose & *alii*, 1999). The effects of these changes in local climate were different on the landscape evolution, depending on the time and number of cycles of exposure to alternating rhexistatic and biostatic conditions. The continuous increase of relief energy controlled by the regional uplift, the base level oscillation, and the repeated climate changes were responsible altogether for the different degree of degradation of the *Calcarenite di Gravina* at the foot of the Murgia escarpment and seaward, and for the alteration and erosion of the Middle Pleistocene raised marine deposits. In the same period, continental water cut an exoreic network of sapping valleys (Mastronuzzi & Sansò, 2002a). At the foot of the Murgia escarpment, the original flight of raised terraced marine deposits was thus eroded, simulating a mechanism responsible for a «like pedimentation» (sensu King, 1968; Twidale, 1968) in a warm/humid-cold/dry climate alternance (fig. 12).

A distinct morphogenic period, intense but spatially and temporally limited, occurred during the Late Interglacial (= MIS 5). In the study area, it is witnessed by two transgressive/regressive episodes (Mastronuzzi & *alii*, 2002) (fig. 12). The first episode is related to a 2-4 m elevated, relative sea-level highstand; it caused the cutting of a platform and a low cliff in the Upper Pliocene-Lower Pleistocene calcarenites or in the overlying red soil, and the sedimentation of beach-dune deposits up to 17 m high (**d1**/**d2**) covering the beach sediments and the cliff and causing the obstruction of stream mouths. The second and smaller transgressive episode caused the development of a continuous dune belt (**d3**) and the formation of backdune depressions, subsequently filled by red continental sands (**d4**).

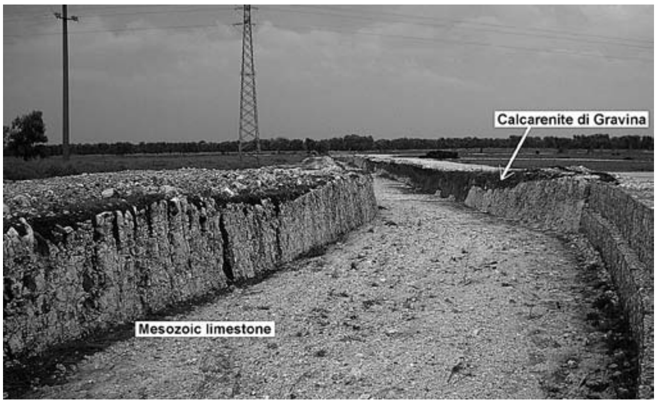


FIG. 12 - The «pediment like» surface, shaped on the Mesozoic limestone and on the Plio-Pleistocene *Calcarenite di Gravina* units of the local basement.

3 - RELATIVE SEA-LEVEL CHANGES AND COASTLINE EVOLUTION

The deep erosion of the surfaces at the base of the Murgia escarpment prevents any detailed reconstruction of the different sea-level stillstands that occurred during the Middle Pleistocene. On the contrary, the length of the last interglacial dune belt allows to reconstruct the related coastline with good approximation. The modern and the last interglacial coastlines are almost parallel, since the first one runs a few hundred meters seaward along the tract Torre Canne-Rosa Marina. In contrast, between Rosa Marina and Torre Guaceto, the two coastlines almost coincide. Elsewhere, e.g. in locality Torre Guaceto-Posticeddu, two different dune belts can be easily recognised. Based on the local stratigraphy, it is clear that these two coastlines correspond to two distinct phases of the sea-level stillstand that occurred during the LIT. Unfortunately, the lack of geochronological constraints does not allow ascribing them to any specific substage within the MIS 5. Both innermost beach and dune deposits, interpreted with good approximation as the maximum trasnsgressive limit, show their base at an elevation corresponding at, or lower than, the LIT eustatic sea level, between 1.5 and 5 m a.p.s.l. This suggests a possible local tectonic subsidence with respect to the eustatic sea level estimated at 7±1 m a.p.s.l. (e.g.: Ferranti & *alii*, 2006) in the southernmost area of Apulia (Mastronuzzi & *alii*, 2007). From Torre Guaceto to Punta Penne, the present-day coastline is set back from the previous one, as suggested by a sequence of little islands offshore Torre Guaceto (Scogli di Apani, Pedagne islands). They consist of beach and dune sediments correlated to the lowermost deposits ascribed to MIS 5 (5.3?). Besides, a further continuous dune belt can be found inland and correlated with the highest of the MIS 5 (possibly MIS 5.5) stillstand. These dune belts were eroded and separated from the land during the fast mid-Holocene transgression, when sea-level reached quickly the present-day position 4,000 years BP (fig. 11) (Scarano & *alii*, 2008).

GEODYNAMIC IMPLICATIONS AND CONCLUDING REMARKS

The integrated dataset collected allow us to trace the evolution until the Middle Pleistocene of the coastal areas northwest and southeast of Canale Reale, i.e. of the Soglia Messapica, which marks the boundary between the Murge plateau (horst) and the Taranto-Brindisi plain (graben). During the Early Pleistocene, the *Calcarenite di Gravina* was deposited to the northwest of the Soglia Messapica, whereas sandy clays belonging to the *Argille subappennine* accumulated to the southeast. During the Middle Pleistocene, a sequence of marine surfaces developed on the calcarenite and green sandy-clays followed by yellow sands onlapped the Argille subappennine. In this long time span, the region North of the Soglia Messapica underwent uplift, whereas the region South of it was in relative subsidence. We interpret the different tectonic behaviour as responsible for the different stratigraphic and morphologic features also associated with sea-level changes (fig. 11).

From a structural point of view, the oldest deformational event found (fig. 9a) is referred to the early/middle part of the Middle Pleistocene. In the same lapse of time, the Southern Apennines chain and related foreland were just undergoing a geodynamic change. The oldest deformational event could be thus interpreted as the final response of the foreland to the contractional regime responsible for the last motion of the Southern Apennines front. Alternatively, we are dealing with the first evidence of the incipient, new tectonic regime that, in the analysed part of the foreland, would be characterized by an extensional stress field with high values of the R ratio. The penultimate event is referred to the latest Middle Pleistocene and is characterized by a SW-NE extension accompanied by high R values (fig. 9b). This is not surprising: for instance, NW-SE graben structures involving Plio-Quaternary deposits off-shore, southeast of the Salento peninsula, have already been described by Argnani & *alii* (2001). They interpret this deformation as an outer-arc extension due to the flexure of the Adriatic foreland. Indeed, all available geodynamic models justify a SW-NE active extension in the study area. Our data confirm this extension and supply new chronological constraints for its activity. In this general frame, the local complexity suggested by the morphotectonic analysis could be possibly explained by the southeastern shift of the peripheral bulge associated with the subduction of the Apulian foreland. The lateral position of the Apulia ridge within the entire slab hinge could have induced a diachronous bending of the lithosphere from the NW to SE.

Since Late Pleistocene onwards, the two areas North and South of the Soglia Mesapica show the same morphological and stratigraphical evolution, characterised by the development of a Tyrrhenian backdune-dune-beach system; both areas are stable or locally affected by limited subsidence.

During the entire time interval between Middle Pleistocene and present, almost the entire study area was emerged and subject to an alternance of rhexistatic and biostatic conditions related to climatic changes. The first condition causes the increase of relief energy due to the sea-level retreat. In this period, all the foothills of the Murgia escarpment were deeply eroded by areal erosive processes controlled by discontinuous water flows. Here, a seaward gently sloping, poliphasic, «pediment like» surface was shaped (fig. 12).

Altogether the morphological and geological data collected suggest that, while in areas closer to the Apennines front the change of tectonic behaviour began in Middle Pleistocene, in the studied area a behaviour change occurred later and quickly, during and after the Last Interglacial period. This circumstance is in accordance with what suggested by the mesostructural analysis, which allowed assigning to the Late Pleistocene the youngest tectonic event defined. As stated before, this event possibly reflects the superficial active stress field still pervading our study area. It is characterized by a horizontal, almost radial extension (*viz.* comparable $\sigma 2$ and $\sigma 3$), emphasized by

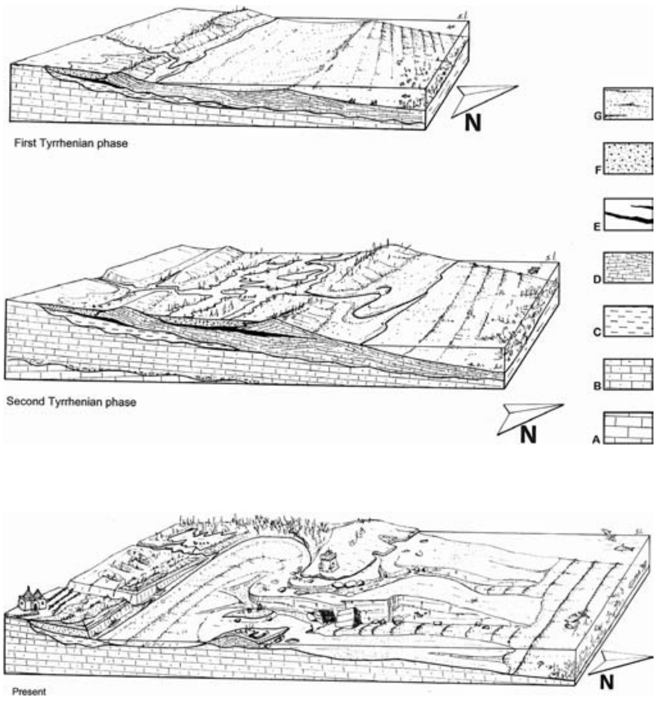


FIG. 13 - Block diagram of the coastal landscape evolution near Torre Guaceto. Legend: A) *Calcare di Bari*; B) *Calcarenite di Gravina*; C) sandy clays; D) MIS 5 beach calcarenites and aeolianites; E) Colluvial deposits; F) MIS 5 backdunes continental red sands; G) Greek-Roman Age aeolianites.

the high angular deviation of σ2 and σ3 (±54° in both cases), which shows that the horizontal axes are interchangeable. Therefore, if we compare this sort of 'doming' of the study area with the previous deformational event, we have to hypothesize a Late Pleistocene stress field variation which encompasses a relative decrease of the σ2 with respect to the σ3. This occurrence is well compatible with the stability, or the homogeneous subsidence, essentially affecting both areas to the north and south of the Soglia Messapica since the Late Pleistocene (fig. 12). This kind of evolution and the final doming observed suggest a geodynamic setting where two orthogonal engines compete. Taking into account the first order geodynamic features summarised in subsection 2.1 Regional Geology, the two suggested engines ("tectonic genetic components"; Caputo, 2005) could be tentatively found on the one hand in the Calabrian Arc (in particular its lateral portion within the Taranto Gulf) and the opposing Dinarides-Albanides-Hellenides chain (this would also explain the local subsidence observed along the Adriatic side of our study area), and on the other hand in the NW-SE Eurasia-Nubia convergence. The different intensity of the movements induced by the two competitive engines could justify the difference in southern Apulia behaviour between the Adriatic, homogeneous stability or low rate of subsidence, and Ionian side, differential uplift rate decreasing from NW to SE. Together, they could provide the competing horizontal stresses needed to determine the observed deformation.

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