

MIDDLE-LATE PLEISTOCENE UPLIFT OF PUGLIA: AN «ANOMALY» IN THE APENNINIC FORELAND (*)

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ABSTRACT

The Apenninic foreland shows two distinct structural signatures comparing the central Adriatic Sea and the Puglia region, located northward and southward respectively along strike in the foreland. During the Neogene, the foreland underwent high subsidence rates (>1mm/yr) due to the eastward rollback of the hinge of the west dipping Apenninic subduction. During the Middle-Late Pleistocene the Puglia region and the Bradanic foredeep, in contrast with the central Adriatic, underwent uplift (0.5mm/yr). The geometry and the kinematics of the related frontal accretionary wedge changed as well: at the front of the central northern Apennines, off scraping and subsidence continued, whereas the foredeep and foreland of the southern Apennines were buckled. Those differences are interpreted as being due to the larger subduction hinge rollback rate since middle Pleistocene of the central Adriatic lithosphere (70 km thick) with respect to the thicker Puglia (110 km). The different thicknesses appear to have controlled the variable degree of flexure of the lithosphere and its asthenospheric penetration rate. The Tremiti E-W alignment is the right-lateral lithospheric transfer zone of those different tectonic regimes.

KEY WORDS: *Apenninic foreland, Puglia uplift, west-dipping subduction, Middle-Late Pleistocene.*

RIASSUNTO

Confrontando il settore centro-adriatico con quello pugliese, si osserva come nelle due aree l'Avampaese apenninico possiede due differenti stili strutturali ed un diverso comportamento geodinamico: in particolare, nel Pleistocene medio-superiore, mentre il settore centro-adriatico manifesta chiari fenomeni di subsidenza il settore pugliese è in netto sollevamento.

Numerose indicazioni di tipo geologico-stratigrafico e strutturale indicano che, per tutto il Neogene,

l'avampaese apenninico abbia avuto un comportamento geodinamico non così diversificato, registrando da nord a sud intensi tassi di subsidenza (>1mm/a) indotti dalla subduzione della placca adriatica immergente a ovest e dal conseguente arretramento flessurale verso est di quest'ultima. Questa tendenza è proseguita anche durante il Plio-Pleistocene, ma dal Pleistocene medio il comportamento geodinamico del settore pugliese si è diversificato rispetto a quello del settore centro-adriatico. In pratica, mentre quest'ultimo ha continuato a registrare tassi di subsidenza comparabili ai precedenti, sia l'Avampaese pugliese che la Fossa bradanica hanno iniziato a subire un marcato sollevamento (0,5mm/a), anomalo sia rispetto al comportamento dell'avampaese nel settore centro-adriatico che nel settore ionico. Nello stesso periodo si sono anche diversificati la geometria e la cinematica del prisma frontale di accrezione relativo ai diversi settori di avampaese, molto meno pronunciato nel settore Bradanico. Questa differenza di stile strutturale viene interpretata come il prodotto di una minore penetrazione della spessa litosfera continentale pugliese rispetto ai settori adiacenti Adriatico a nord e Ionico a sud. Il rialzo della litosfera pugliese può così essere interpretato come un piegamento litosferico indotto dalla spinta relativa verso est del mantello astenosferico che agisce sul piano di subduzione al di sotto degli Apennini. L'allineamento strutturale E-W delle Tremiti appare come lo svincolo tra i due stili geodinamici: il maggiore arretramento verso est della litosfera adriatica rispetto a quella pugliese è acconsentito dal trasferimento destro lungo la lacerazione litosferica delle isole Tremiti.

TERMINI CHIAVE: *Avampaese adriatico, sollevamento Puglia, subduzione apenninica, Pleistocene medio-superiore.*

INTRODUCTION

The geodynamics of the Apenninic foreland is an issue that received particular attention in the last years (e.g. KRUSE & ROYDEN, 1994). The main force controlling the bending of the subducting Adriatic plate underneath the Apennines has been interpreted as due to either slab pull (ROYDEN *et alii*, 1987) or slab pull and «eastward» relative mantle flow

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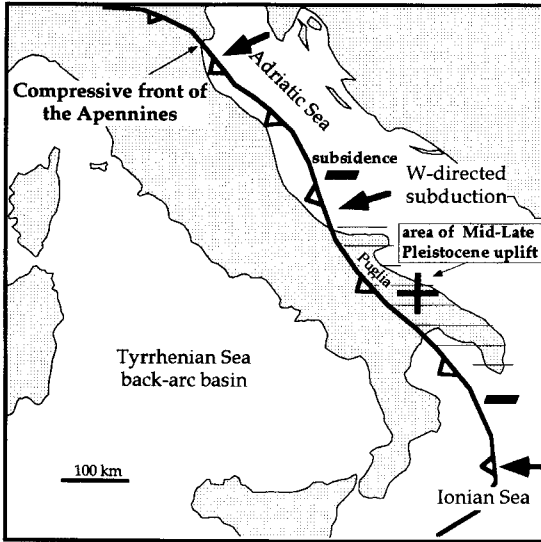


Fig. 1 - During the Middle-Late Pleistocene the Apenninic foreland has been uplifting in the Puglia region (+) and subsiding in the adjacent Adriatic and Ionian seas (-).

(DOGLIONI, 1991; 1994). This paper aims to integrate the interpretation of the anomalous Middle-Late Pleistocene uplift of the Apenninic foreland in Puglia and Bradanic foredeep of southeast Italy (fig. 1) proposed by DOGLIONI *et alii* (1994). This recent uplift has been documented by several Authors (e.g. CIARANFI *et alii*, 1983; DAI PRA & HEARTY, 1988) and it contrasts with adjacent foreland areas such as the central and northern Adriatic or Ionian seas where subsidence occurred at the same time (e.g. FINETTI, 1982; COLANTONI *et alii*, 1989). This paper would like to show that this different geodynamic behavior is related to the different amount of subduction hinge rollback controlled by the different thicknesses and composition of the Adriatic plate in subduction underneath the Apennines.

REGIONAL SETTING

The Puglia foreland region is often geologically named Apulian platform, because of the widespread occurrence of the Mesozoic carbonate platform in this area. This region is deformed by a 100 km broad WNW-ESE trending antiform, from the Bradanic fore-

deep to the west and the Adriatic basin to the east (RICCHETTI & MONGELLI, 1980). This antiform structure is a different one with respect to the Cretaceous anticline, as proposed by RICCHETTI (1980).

NW-SE-trending normal faults outcrop in Puglia and eastern Bradano trough (CIARANFI *et alii*, 1983; RICCHETTI *et alii*, 1988). They have variable ages, likely from the Mesozoic to the Pleistocene. They dissect the entire Puglia antiform, but also the submerged Apulian swell to the southeast (AUROUX *et alii*, 1985). The Puglia antiform shows down faulted blocks both toward the Bradanic trough to the west and toward the Adriatic (CARISSIMO *et alii*, 1963; PIERI, 1980; RICCHETTI, 1980). Transfer faults striking oblique or perpendicular to the main WNW trending normal faults segmented the Puglia in three main blocks with different degree of uplift (from the highest Gargano, Murge, and to the lowland of Salento toward the southeast) (RICCHETTI *et alii*, 1988; FUNICIELLO *et alii*, 1991). Normal and transtensional faults were active during the Plio-Pleistocene in the eastern margin of the Bradano foredeep as indicated by syn-tectonic deposits west of Matera (TROPEANO *et alii*, 1994) and, in the shelf, west of Salento area (TRAMUTOLI *et alii*, 1984).

According to ZAPPATERRA (1994) the passive margin-related Jurassic-Cretaceous stratigraphy of the Apenninic foreland shows a system of carbonate platforms (Apulian and Dinaric-Dalmatian) separated by a basin (Adriatic-South Adriatic or Ionian and Umbria Marche). The active margin stratigraphy recorded in the Apenninic foreland shows a Neogene «eastward» migration of the foredeep depocenter. The subsidence was controlled by the eastward rollback of the subduction hinge of the Adriatic plate (MALINVERNO & RYAN, 1986). During the Pliocene-Early Pleistocene a comparable structural and sedimentary evolution, with high subsidence rates (>1mm/yr) characterized the Apenninic foredeep both in the Po basin, northern Adriatic sea and the Bradanic foredeep (CASNEDI *et alii*, 1982; BIGI *et alii*, 1989; ORI *et alii*, 1991). In the Ancona offshore (fig. 2) Plio-Pleistocene sediments overly the Mesozoic-Early Tertiary succession with more than 1600 m of Quaternary clastics (PACCHIAROTTI, 1982).

The Pliocene-Early Pleistocene Argille subappennine filled the Bradanic foredeep at the front of the southern Apennines, showing

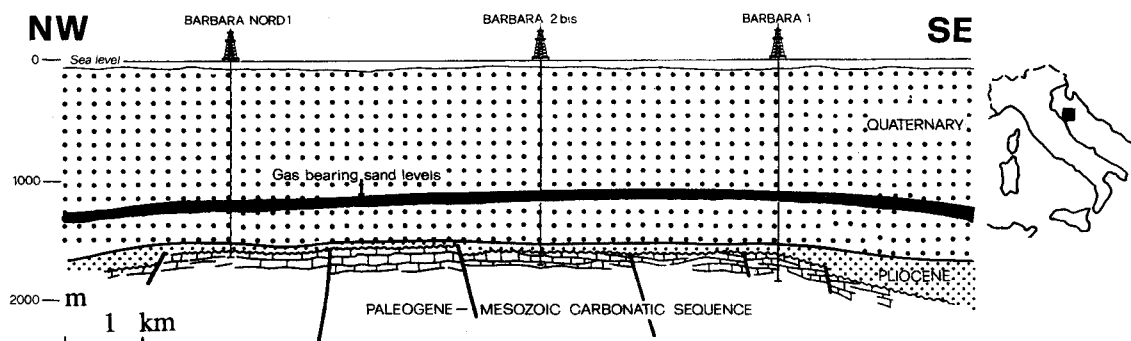


Fig. 2 - Cross-section of the Barbara field in the central-north Adriatic sea, 55 km northeast of Ancona, after PACCHIAROTTI (1982). Note the more than 1500 m thick Quaternary sequence.

an «eastward» migration of their depocenter (CIARANFI *et alii*, 1979; CASNEDI, 1988a; 1991), like the coeval sediments all around the Apenninic arc (BOCCALETTI *et alii*, 1990). Therefore the Puglia region and the Bradanic foredeep underwent subsidence during the Pliocene and the Early Pleistocene like the adjacent Adriatic and Ionian seas. However, since the Middle Pleistocene, the Puglia foreland and the Bradanic foredeep in front to the Southern Apennines, began to uplift (CIARANFI *et alii*, 1983), in contrast with the northern foreland in the central Adriatic or the Ionian sea where subsidence continued regularly (BIGI *et alii*, 1989; COLANTONI *et alii*, 1989). In contrast with the stratigraphy of the northern-central Adriatic where a thick pile of clastic Pleistocene sediments accumulated (PACCHIAROTTI, 1982; DOULCET *et alii*, 1990) (fig. 3), in the Puglia region thin outcrops (a few tens of m) of Late Pliocene-Early Pleistocene calcarenites (which overly the Cretaceous carbonate platform sediments) are only locally preserved by the erosion where Middle-Late Pleistocene uplift occurred (IANNONE & PIERI, 1979; 1982) (fig. 4).

The impressive difference between the two realms is underlined by the active subsidence in the Adriatic sea (COLANTONI *et alii*, 1989) and by the coeval uplift to the south in the Bradano trough and in Puglia foreland (DAI PRA & HEARTY, 1988). Several workers point out the evidences for this uplift, particularly in the Murge and in the close foredeep area, corresponding to the southern sector of the Bradano trough, the so called «Bacino Lucano». In this area, the sediments which deposited in the Bradano trough until the

Early Pleistocene are outcropping, e.g. the Late Pliocene-Early Pleistocene prodelta-shelf emipelagites («Argille subappennine» *Auctt.*) (fig. 5) and the overlying Early Pleistocene coastal deposits, that at present are at about 5-600 m of altitude («Sabbie di Monte Marano» and «Conglomerato di Irsina» *Auctt.*; informally redefined as «Genzano and Irsina coastal deposits» by PIERI *et alii*, 1994).

The uplift of the Bradano trough is better evidenced by the presence of several NW-SE prograding marine terraced deposits, that disconformably overlay the Argille subappennine to the south-east of Ferrandina and Miglionico localities («Depositati marini terrazzati» of: VEZZANI, 1967; COTECCHIA & MAGRI, 1967; RICCHETTI, 1967; 1972; BOENZI *et alii*, 1971; 1976; BRÜCKNER, 1980a; 1980b; PAREA, 1986; DE MARCO, 1990). Altitudes and ages of these deposits decrease from about 430-400 m, close to Pomarico and Matera localities, to a few metres above sea level, close to the Ionian coast. The higher terraces, begun to sediment shortly before the Matuyama-Brunes inversion (BRÜCKNER, 1980a) and containing the older «Monte Vulture» volcanoclastic products (DE MARCO, 1990) (1), are Middle Pleistocene in age; the younger marine terraced deposits have been dated with radiometric methods, and they are Tyrrhenian (*s.l.*) in age (COTECCHIA *et alii*, 1969; COSENTINO & GLIOZZI, 1988; DAI PRA & HEARTY, 1988; HEARTY & DAI PRA, 1992 and cited references).

(1) The «Monte Vulture» volcanic activity began 730±20 ky.a. (VILLA, 1985).

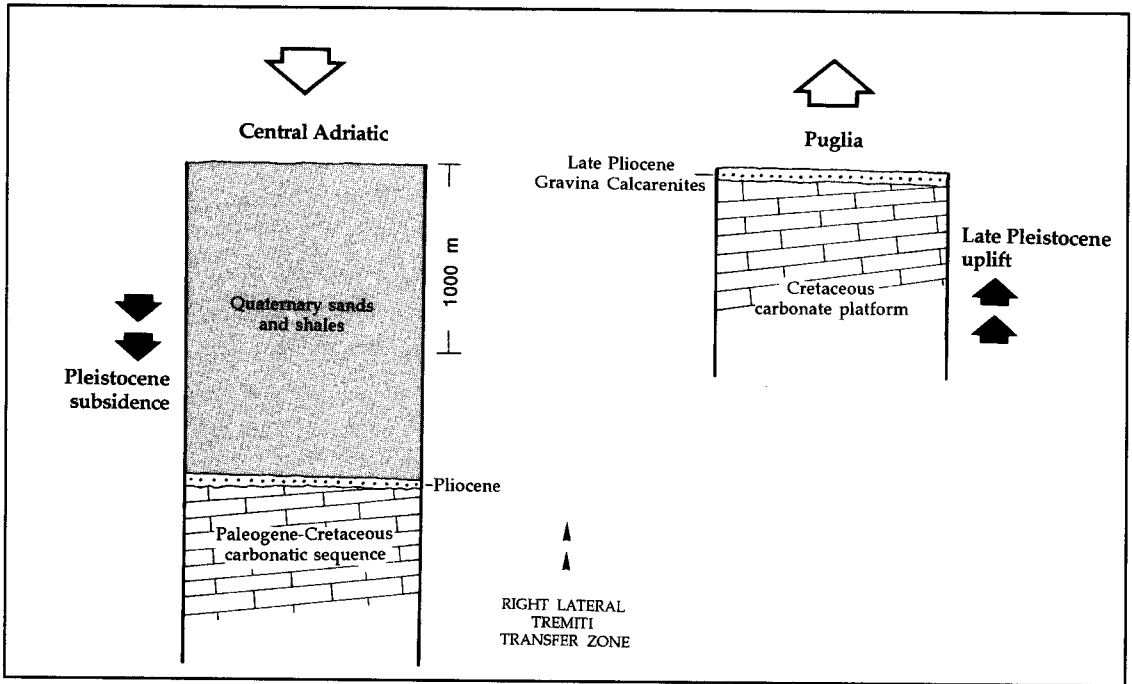


Fig. 3 - Schematic stratigraphic columns of the Apenninic foreland in the northern-central Adriatic and Puglia. The Pliocene discordantly overlies Paleogene or Cretaceous successions in both sections. In the Adriatic the subsidence developed throughout the Quaternary, whereas the Puglia region underwent uplift during the Middle-Late Pleistocene.



Fig. 4 - The Late Pliocene-Early Pleistocene Gravina Calcarenes (G) discordantly overlies the Early Cretaceous Calcare di Bari (B) near San Giorgio (south of Bari, few meters above sea level). This outcrop is emblematic of the stratigraphy of the Murge-Puglia area in the Apenninic foreland which is in uplift since Middle Pleistocene.

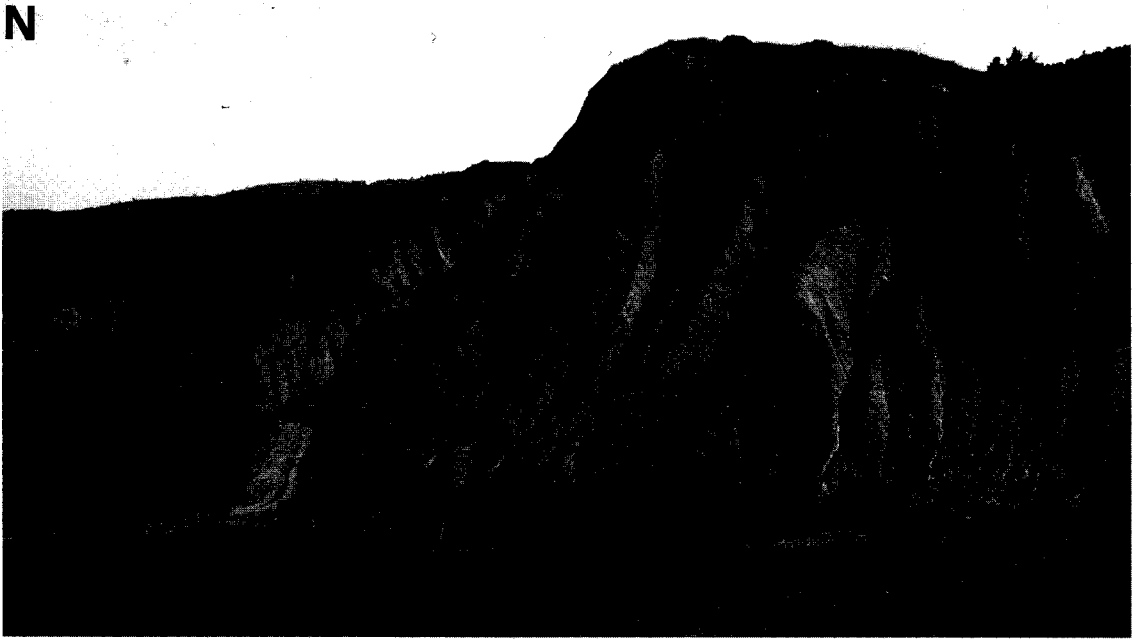


Fig. 5 - Uplifted Early Pleistocene Argille Subappennine near Ferrandina in the Bradanic foredeep.

The uplift of the Murge is testified by the presence of 16 orders of uplifted shorelines, recorded by palaeocliffs, abrasion platforms, and/or by thin marine terraced deposits, that disconformably overlay the Mesozoic limestones and the thin Late Pliocene-Early Pleistocene units of the Murge (CIARANFI *et alii*, 1988) (fig. 6). All around the «Murge Alte» that represent the ridge of the Murge and show mature karstic features, the older and higher shoreline is recorded by a cliff, somewhere with eolianites at the foot; the «Murge Alte» ridge was never drowned by the «foredeep sea», and the higher shoreline marks the end of the Apulia foreland subsidence in the Murge area (IANNONE & PIERI, 1982). As well as in the Bradano trough, altitudes and ages of the uplifted shorelines of Murge decrease from about 450 m to a few metres above sea level (from Middle Pleistocene to Tyrrhenian *s.l.* in age, according to CIARANFI *et alii*, 1994); a comparable trend may be observed in Salento (D'ALESSANDRO *et alii*, 1987; CIARANFI *et alii*, 1988). According to Late Pleistocene geochronological data, uplift rates are in the order of 0.2-0.3 mm/yr (COSENTINO & GLIOZZI,

1988; DAI PRA & HEARTY, 1988; 1989). However stratigraphic data suggest uplift rates of at least 0.5 mm/yr (CIARANFI *et alii*, 1994). Late Pleistocene fluvial terraces, particularly related to the Basento and Bradano rivers, and deep incised valleys either in the Bradano trough or in Puglia, where these canyons are locally called «gravine», testify the recent high uplift rates in the south-Appenninic foreland.

In short, in the Murge, the older morphological and geological records of the uplifted shorelines show good topographic and chronologic correlations with the higher marine terraced deposits of the Bradano trough (fig. 6, A); the younger records, i.e. the marine terraced deposits close to the Taranto coast, show to be continuous with the marine terraced deposits of the Bradano trough (RICCHETTI, 1967; 1972; BRÜCKNER, 1980a; 1980b) (fig. 6, B). Moreover, the shoreline altitudes decrease from the «Murge alte» (as well as from the ridges of the Salento area) either toward the Ionian sea or toward the Adriatic sea; this shows the progressive uplift of the Puglia foreland antiform.

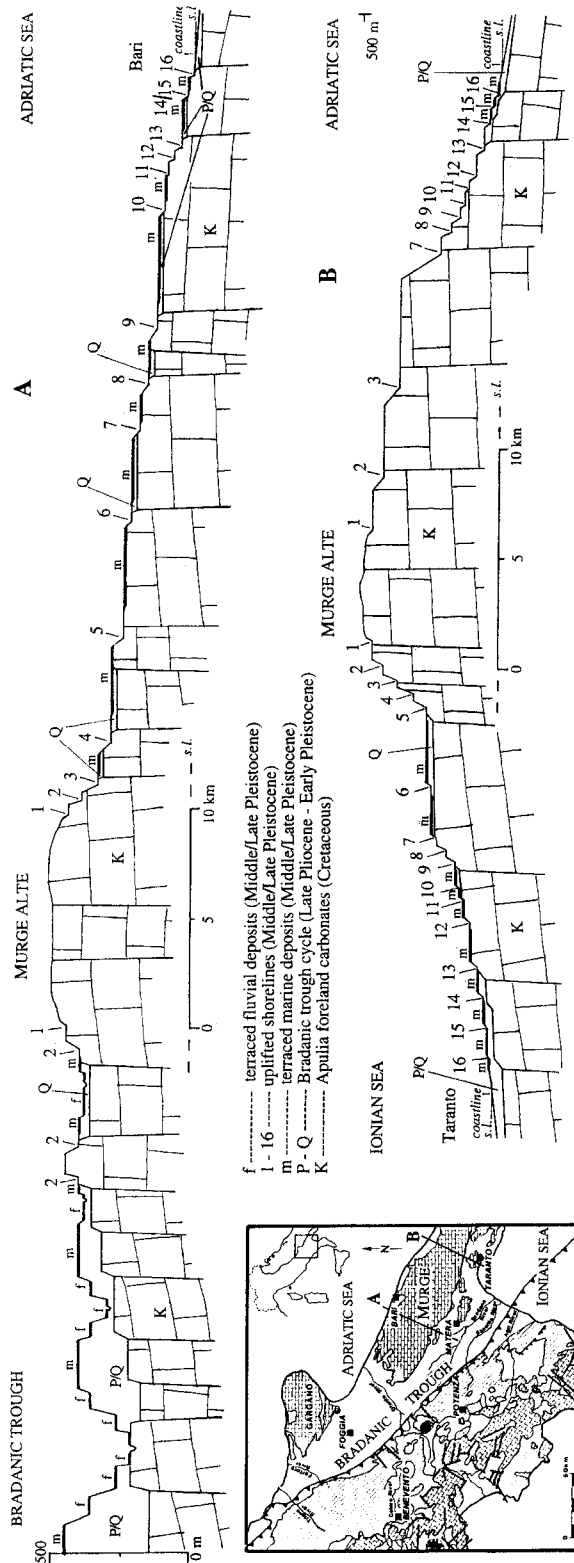


Fig. 6 - Schematic sections across the Apulian foreland antiform in the Murge area. Note the 16 different orders of terraces indicating the Middle-Late Pleistocene uplift. Data from: RICCHETTI (1967; 1972; 1980); BRÜCKNER (1980a); MONGELLI & RICCHETTI (1980); PIERI (1980); IANNONE & PIERI (1979; 1982); RICCHETTI *et alii* (1988); CIARANFI *et alii* (1988; 1994).

EASTWARD ROLL-BACK OF THE APENNINIC SUBDUCTION HINGE

It is widely accepted that the Apennines formed while the subduction hinge of the Adriatic plate rolled back toward the east (MALINVERNO & RYAN, 1986; ROYDEN *et alii*, 1987; DOGLIONI, 1991), and several structural, volcanic and geophysical evidences show that subduction is still active (in accordance with AMATO *et alii*, 1993 and cited references). Subduction is notoriously controlled by the negative buoyancy of the lithosphere which varies as a function of thickness and composition. The different behavior of the Apennines foreland, between Puglia and the central Adriatic occurs at the transition between the thin continental lithosphere of the Adriatic (70 km) and the thicker continental lithosphere of Puglia (100-110 km, according to the data of CALCAGNILE & PANZA, 1981, fig. 7). To the southwest of Puglia oceanic lithosphere has been detected in the Ionian sea (DE VOOGD *et alii*, 1992) which is definitely more subductable with respect to the thick continental Puglia lithosphere. These differences must control the subduction rate around the Apenninic arc, determining variable degrees of subduction hinge roll-back (fig. 8). This is particularly true in the three different zones (central Adriatic, Puglia and Ionian sea), being the Puglia region positioned between two areas of more subductable lithosphere. This could explain why the subduction hinge zone advanced more toward the northeast in the central-northern Adriatic sea, and toward the southeast in the Ionian sea with respect to the Puglia where it occurs the thickest continental segment of lithosphere. The lower subduction rate that developed west of Puglia during the Middle-Late Pleistocene appears to be compensated by the buckling of the lithosphere which becomes the reason for the recent uplift of the foreland and the antiformal geometry of Puglia (fig. 8). The antiformal geometry of the foreland is a sort of bulge (RICCHETTI & MONGELLI, 1980) just adjacent to the subduction hinge which is anomalous both in terms of Apenninic geodynamics and other reported bulges of the western Pacific. The peculiar antiformal in front to the southern Apennines is also depicted by the gravity anomalies in the Apenninic foreland. The gravimetric profile of the Puglia-Southern Apennines section (fig. 9) shows a bulge

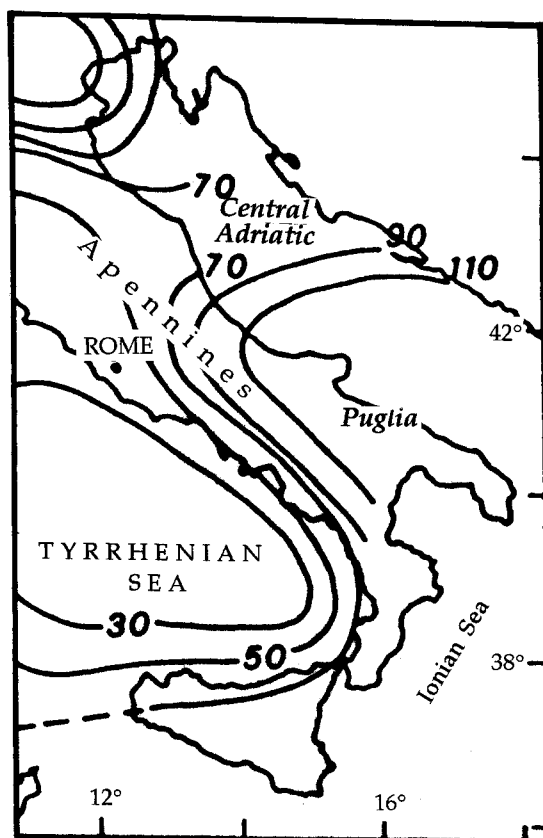


Fig. 7 - Lithospheric thicknesses of the Apennines, Puglia and Adriatic sea region, after CALCAGNILE & PANZA (1981).

which is absent in the adjacent sectors where there occur smoother gravimetric profiles. Moreover this anomalous profile indicates that the subduction hinge zone is more to the west in the Southern Apennines section with respect to its counterpart to the north where the subduction hinge traveled more to the east. The bulge of the foreland in Puglia could be responsible also for the anomalous uplift of the Moho underneath the Gargano which is paradoxically the highest morphologic peak of the foreland. The Puglia continental lithospheric thickening appears to be aligned obliquely (N50°W) with respect to the front of the Apennines and the subduction hinge (N30-40°W). This could explain the larger and earlier uplift of northern Puglia which arrived earlier at the subduction hinge with respect to

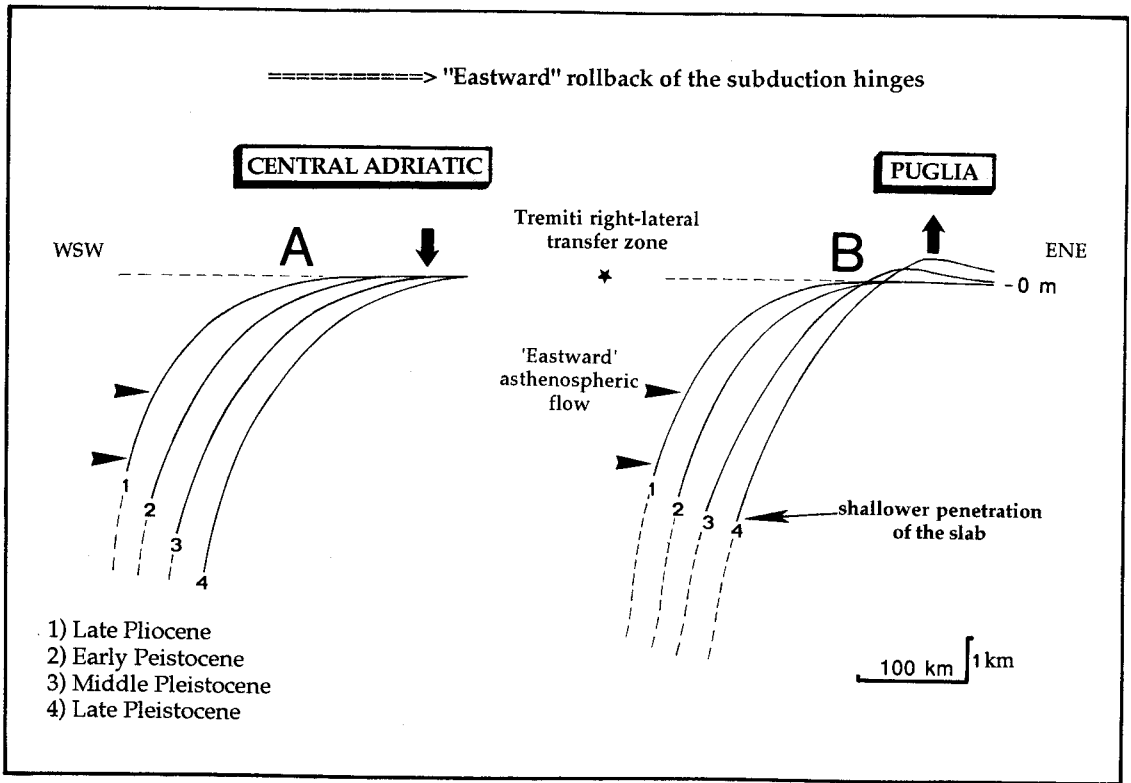


Fig. 8 - Comparison of the different evolution of the subduction hinge rollback of the central Adriatic and Puglia. The existence of Puglia, as present land, may be interpreted as due to the uplift of the lithosphere as a consequence of the lower penetration of the slab, due to the thicker continental lithosphere arrived at the subduction; this is compensated by buckling of the lithosphere (after DOGLIONI *et alii*, 1994).

the southeastern side of the region which is less elevated. Therefore the uplift of Puglia appears to be a lithospheric problem linked to different rates of eastward roll-back of the subduction hinge (fig. 10).

An eastward moving asthenosphere relative to the lithosphere is evidenced by the hot-spot reference frame and the asymmetry among orogens related to opposite subduction zones (DOGLIONI, 1991; 1993). This implies that there should be an eastward oriented push acting on the Adriatic slab at depth (figs. 8 and 10). This means that, besides the forces generally considered in the study of the flexural behavior of the lithosphere (i.e. slab pull), this other force should be taken into account MONGELLI *et alii* (1994). The «eastward» directed asthenospheric flow may be responsible for the buckling of the southern Apennines-Puglia lithosphere, due to its reduced penetration rate. This localized buckling could be the

responsible for the uplift of the foreland that is missing in the adjacent Adriatic and Ionian segments.

THE TREMITI TRANSFER ZONE

The larger eastward rollback of the Apenninic subduction hinge in the central Adriatic lithosphere with respect to the Puglia lithosphere (fig. 10) needs a right lateral transfer zone which can be mainly identified with the N80-90°E Tremiti alignment, to the north of the Gargano promontory (fig. 11). These faults are active as indicated by seismicity (FAVALI *et alii*, 1990; 1993; CONSOLE *et alii*, 1993) and young escarpments (ARGNANI *et alii*, 1993). The right lateral motion of all these faults is also marked by the right lateral displacement of the Cretaceous carbonate platform margin both to the north of the Gargano

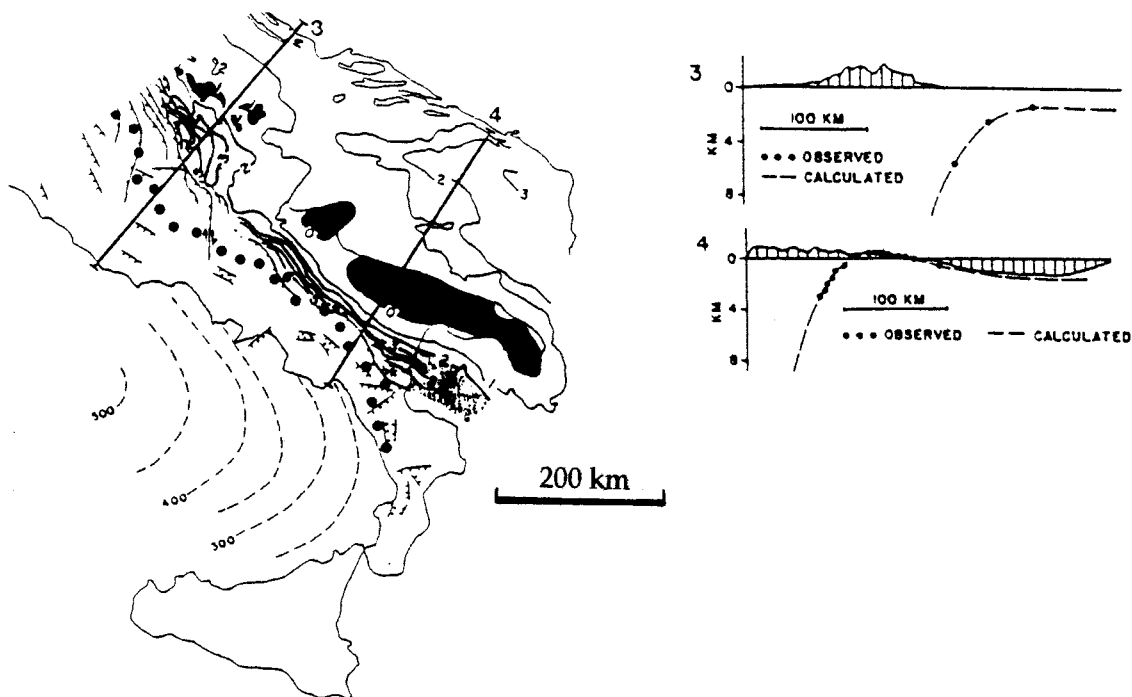


Fig. 9 - Gravimetric profiles in the Apenninic foreland, after ROYDEN *et alii* (1987). Note in the Adriatic northern section the gradual deflection indicating the smooth shape of the subduction hinge. In the Puglia section the profile is marked by a bulge which is also more to the west with respect to the northern profile, underlining the anomalous buckling of the lithosphere. Compare with the previous figure.

promontory and to the south of it (see DOULCET *et alii*, 1990). Field evidences clearly support this sense of shear in the Tremiti islands (fig. 11): E-W trending right lateral transtensional faults cross-cutting Pliocene calcarenites and Late Miocene sandstones («San Nicola», Pliocene, and «Cretaccio», Langhian-Tortonian; CREMONINI *et alii*, 1971) (FUNICIELLO *et alii*, 1988; 1991); sets of en-échelon Riedel shears indicating right lateral sense of motion along E-W trending fault planes in the Eocene Nummulitic limestones of the San Domino Formation and horizontal slickensides on E-W trending faults in the same formation. A lithospheric alignment with similar trend to the north (Pescara-Dubrovnik) has been proposed by GAMBINI & TOZZI (1995).

As a whole, the transfer zone is active in the foreland of the Apenninic front, and it has an eastward propagating tip line in the eastern side of the lower Adriatic basin. In other words, this system of faults exists in order to

accommodate the different behavior of the subduction of the Adriatic plate underneath the Apennines, separating two segments with different rollback rates. This generated different kinematics of the frontal part of the Apennines during the Middle-Late Pleistocene, with a poorly developed accretionary wedge to the east of the Southern Apennines (MOSTARDINI & MERLINI, 1986; CASERO *et alii*, 1988; CASNEDI, 1988b), and an uplift foredeep and foreland, in contrast with the adjacent areas in the Adriatic to the north (SCHWANDER, 1989; ORI *et alii*, 1991) and in the Ionian Sea to the south (FINETTI, 1982). The kinematics of the frontal part of the Apennines are different between Northern-Central Apennines in comparison to the sections of the front of the Southern Apennines, being both fronts alive throughout the Quaternary. This separation between the two structural styles occurs at the dextral undulation of the arc to the west of the Gargano promontory (fig. 10). The most external thrusts of the Apenninic accretionary

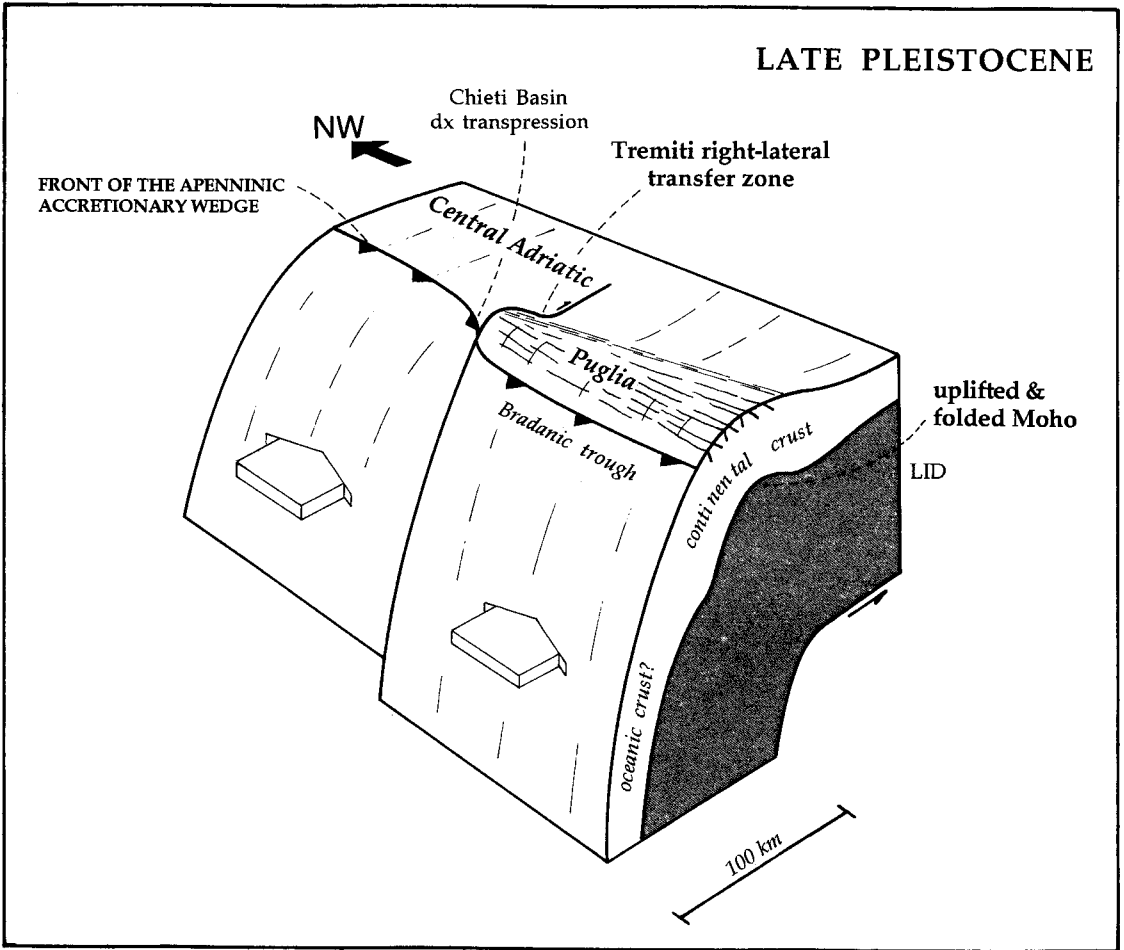


Fig. 10 - Block-diagram showing the different behavior of the Adriatic and Puglia lithosphere. The E-W trending Tremiti tectonic alignment should be the right lateral transfer zone between the larger eastward rollback of the subduction hinge of the Adriatic lithosphere characterized by a thinner lithosphere (70 km) relative to the uplifting Puglia where the lithosphere is thicker (110 km) and shows a lower penetration rate (after DOGLIONI *et alii*, 1994).

wedge are buried in the western side of the central Adriatic, offshore Pescara and Chieti, and they parallel the coast. They deviate southward and enter onshore at the southern margin of the Chieti basin, west of the Gargano promontory. They return to strike NW-SE with the Apenninic trend along the western side of the Bradano foredeep. This undulation

indicates a dextral transpression characterized by oblique ramps at the intersection of the superficial decollements of the accretionary wedge and the E-W-trending Tremiti Line. This is a lithospheric discontinuity (MONGELLI, 1975) separating a thicker lithosphere to the south with respect to its northern counterpart (fig. 7).

Fig. 11 - Evidences of strike-slip tectonics in the Tremiti islands. A) E-W trending right lateral transtensional faults in the San Nicola Island cross-cutting Pliocene Calcarenes and Late Miocene sandstones (at the top San Nicola Formation, Pliocene; at the bottom Cretaccio Formation, Langhian-Tortonian). B) View from the top of a set of en-échelon Riedel shears indicating right lateral sense of motion along an E-W trending fault plane in the Eocene Nummulitic limestones of the San Domino Formation, northern part of the San Domino Island. C) Horizontal slickensides on a E-W trending fault in the Eocene Nummulitic limestones of the San Domino Formation, northern part of the San Domino Island.

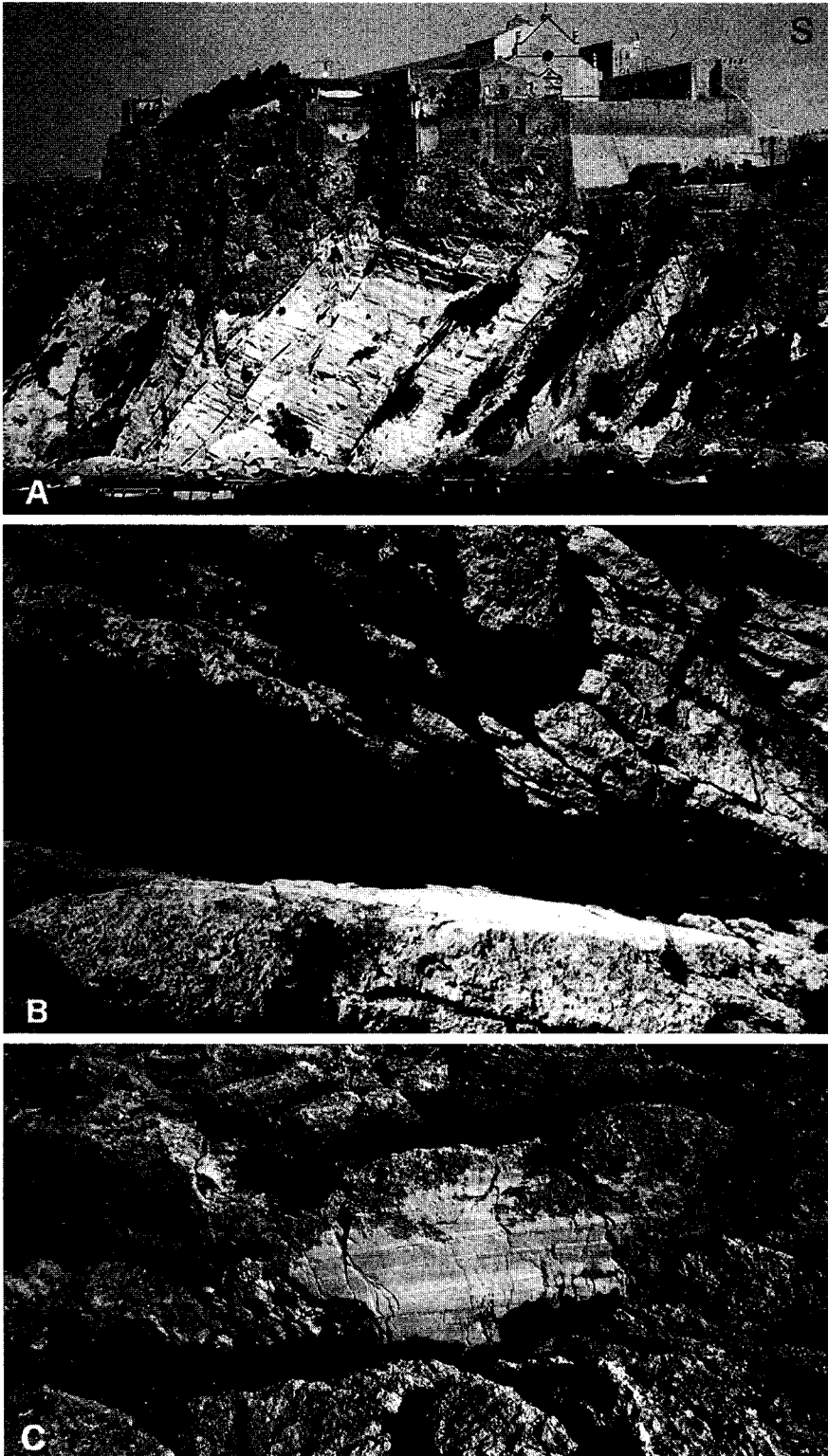


Fig. 11

THE COMPRESSIVE APENNINIC FRONT

To the south of the Tremiti alignment there also is a change in the structural style of the frontal accretionary wedge of the central and southern Apennines. In general, the Apenninic frontal accretionary wedge shows imbricate fan geometries and is largely positioned below sea-level (SCHWANDER, 1989; ORI *et alii*, 1991). Frontal thrusts involve the Quaternary at the buried front of the Apennines in the Po

Plain and in the western Adriatic sea (BIGI *et alii*, 1989). Active thrusting and folding deforming Quaternary sediments are visible at the rear of the accretionary wedge (often running parallel to the base of the eastern Apenninic slope) with out-of-sequence kinematics. The front of the southern Apennines in the western Bradano foredeep shows instead a poorly developed imbricate fan in the Bradano foredeep (see CASNEDI, 1988b), whereas it seems to be active the internal out-of-

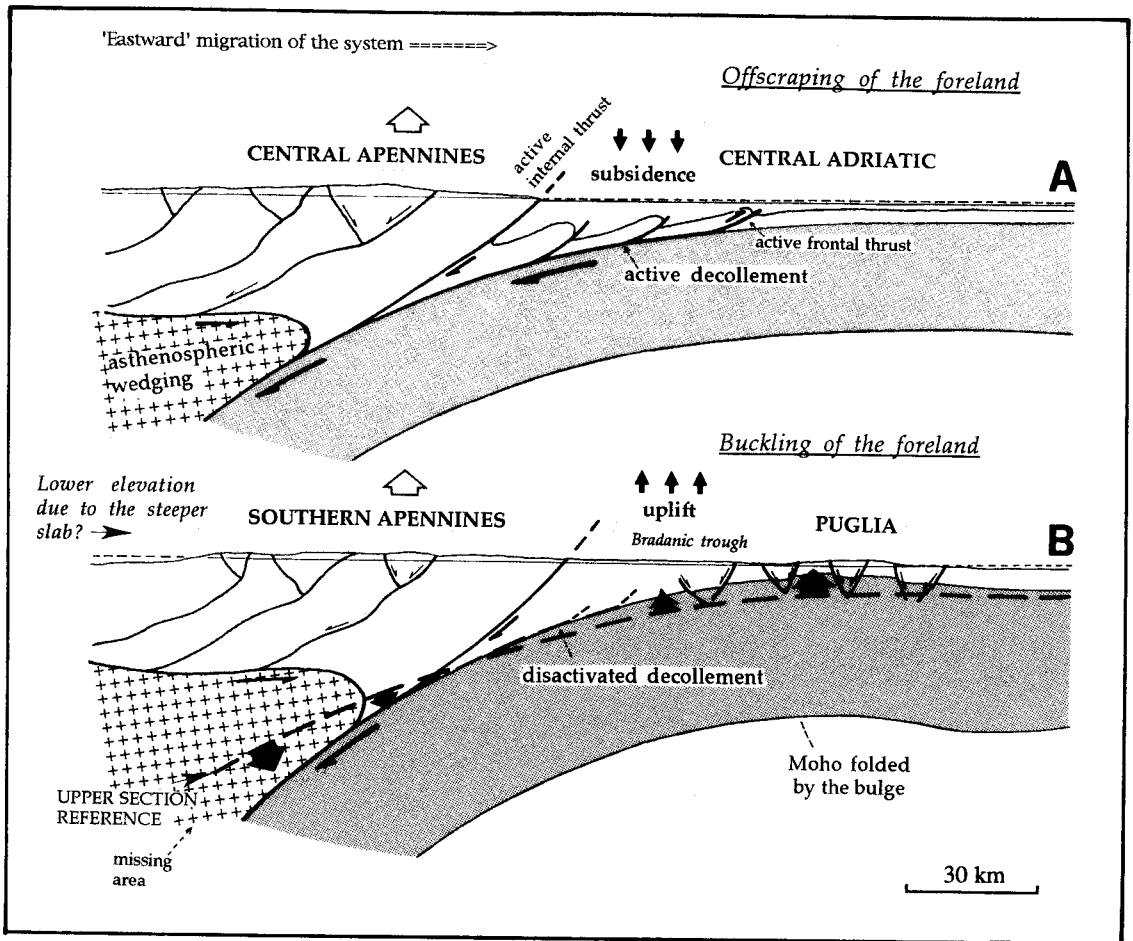


Fig. 12 - During the Middle-Late Pleistocene evolution, the accretionary wedge kinematics differ between the Central-Apennines and the Southern Apennines. In the northern section the accretion continues through offscraping of the upper layers of the 'westward' down going subducting Adriatic plate. In the southern section, the lower rollback of the subduction hinge is compensated by buckling and formation of the Puglia bulge. The uplift involved also the Bradanic trough which underwent subsidence until the Early Pleistocene. The southern section shows a steeper monocline of the top of the subducting plate in depth. This may have controlled the lower elevation of the Southern Apennines due to the wider available room occurring in the hangingwall (after DOGLIONI *et alii*, 1994).

sequence thrust, as documented by deformation of Pleistocene deposits at the western margin of the Bradano foredeep (e.g. the Serra del Cedro conglomerates near Tricarico, LOIACONO & SABATO, 1987).

The buckling of the Adriatic lithosphere has several consequences for the structural evolution of the Southern Apennines: the relative lower subduction with respect to the other Apenninic sectors has to control a lower and smaller decollement of the sedimentary cover in comparison with the other parts of the Apenninic accretionary wedge. In other words the regular offscraping of the sedimentary cover is more inhibited at the front of the Southern Apennines relative to the adjacent areas, due to the lower descent of the lithosphere. Therefore rather than offscraping and active decollements, the front of the Southern Apennines (i.e. the Bradano trough and the Puglia foreland) is characterized by buckling, and the shape and kinematics of the accretionary wedge change with respect to the central northern Apennines and the Ionian arc (DOGLIONI *et alii*, 1994).

The buckling of the foreland is compensated by a steeper slab underneath the Southern Apennines (fig. 10). Considering the shape of the top of the basement, this has a smoother shape in the section between central Apennines and central Adriatic in comparison to the Southern Apennines and Puglia cross-sections (fig. 12). These last sections show a large scale crustal folding (80-100 km large), with a relative uplift of the top of the basement with respect to the central Apennines section. But this uplift is compensated by a deepening of the top of the basement (corresponding to the top of the lithosphere) more to the west underneath the Southern Apennines: this has the consequence to expand the available area above the subduction zone in this section with respect to its northern counterpart (DOGLIONI *et alii*, 1994). The consequence of this larger available room may be the lowering of the entire crust and asthenosphere in the Southern Apennines section, responsible for the lower elevation of the Southern Apennines with respect to the Central Apennines where are located the highest mountains (Gran Sasso, Maiella, etc.), in spite of a smaller subduction. The different rollback rates between the northern and southern sections could explain also the higher heat flow values recor-

ded in the Bradano foredeep with respect to the adjacent cooler foredeep to the north and to the south (MONGELLI *et alii*, 1991); the asthenospheric wedge underneath the Southern Apennines migrating eastward at slower rates could have had more time to heat and to transfer hot fluids to the upper layers than the adjacent sectors, or the concentration of the compressive belt in a more stationary area could have generated a stronger squeezing of the hot deep fluids.

CONCLUSIONS

The Apenninic foreland shows two distinct structural signatures comparing the central Adriatic and the Puglia (or Apulian) region. During the Pliocene-Pleistocene the central Adriatic underwent high subsidence rates due to the eastward rollback of the hinge of the W-dipping Apenninic subduction. The Puglia foreland and the Bradanic foredeep are located southward along strike in the same foreland, but, in contrast with the central Adriatic, they underwent uplift since Middle Pleistocene. The kinematics of the frontal accretionary wedge are also changing from that moment on between the Central-Northern Apennines and the Southern Apennines, being the Tremiti E-W alignment the right lateral transfer zone. Those differences are here interpreted as due to the different subduction hinge rollback rates controlled by the different thickness inherited from the Mesozoic rifting of the down going Adriatic lithosphere (70 km the central Adriatic and 110 km Puglia). The Ionian sea is floored by the heavier oceanic lithosphere enabling easier subduction with respect to the Puglia region. The different lithospheric thickness and composition may have in turn controlled the variable degrees of flexure of the lithosphere and its asthenospheric penetration rates. Therefore the arrival at the subduction hinge of the thick buoyant continental lithosphere should have decreased the rate of penetration at depth of the subduction plane and of the rollback of the subduction hinge along the Southern Apennines. This may have in turn controlled the split of the Apenninic subduction plane into two minor arcs where in the foreland persist lithosphere typologies of larger negative buoyancy, the larger and faster Ionian arc to the south and the northern

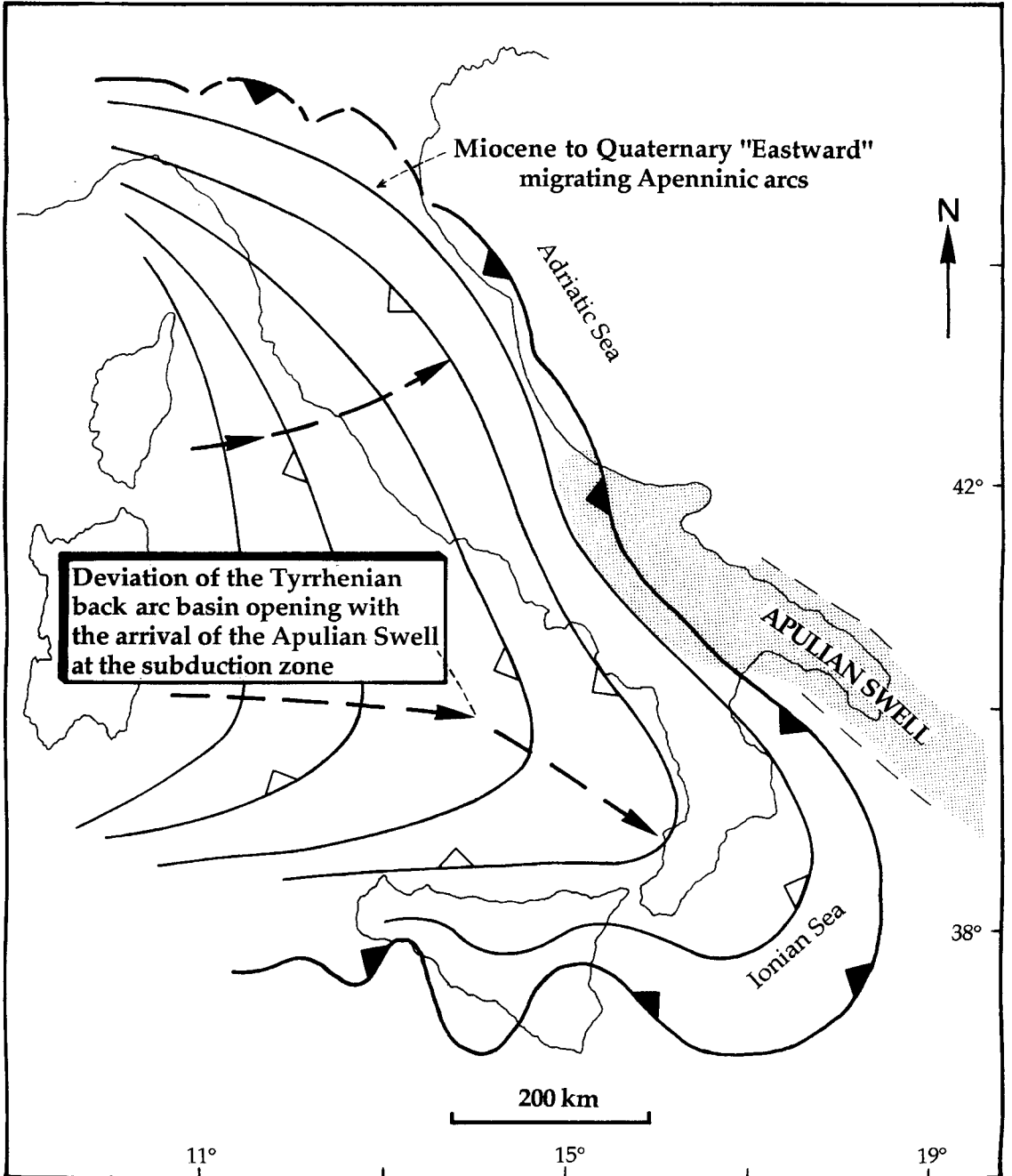


Fig. 13 - The Apenninic arc migrated «eastward» during Neogene and Pleistocene times, associated with the rollback of the subduction hinge. The arrival of the thick continental lithosphere of the Apulian swell to the subduction hinge probably controlled the split in two second order arcs, i.e. the larger southeastward deviation of the Ionian arc and of the Tyrrhenian back arc spreading, and the contemporaneous eastward migration of the central-northern Apennines arc (modified after DOGLIONI *et alii*, 1994).

Apennines arc to the north (fig. 13). A left-lateral transfer zone between the uplifting Puglia and the subsiding Ionian sea is also expected in the Taranto Gulf. Nevertheless this transfer zone should have different characters with respect to the Tremiti alignment because the Apenninic arc rapidly changes direction from NW-SE to NE-SW in the Ionian sea with respect to the front of the southern Apennines, determining an arc where left-lateral motion is naturally expected.

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REFERENCES

- AMATO A., ALESSANDRINI B., CIMINI G., FREPOLI A. & SELVAGGI G. (1993) - *Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity*. *Annali di Geofisica*, **36** (2), 201-214.
- ARGNANI A., FAVALI 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** (2), 229-247.
- AUROUX C., MASCLE J., CAMPREDON R., MASCLE G. & ROSSI S. (1985) - *Cadre géodynamique et évolution récente de la Dorsale Apulienne et de ses bordures*. *Giorn. Geol.*, **47**, 101-127.
- AZZAROLI A., PERNO U. & RADINA B. (1968) - *Note illustrative della Carta Geologica d'Italia, F° 188 «Gravina di Puglia»*. *Serv. Geol. It.*, 1-57.
- AZZAROLI A., RADINA B., RICCHETTI G. & VALDUGA A. (1968) - *Note illustrative della Carta Geologica d'Italia, F° 189 «Altamura»*. *Serv. Geol. It.*, 1-22.
- BALLY A.W., BURBI L., COOPER C. & GHELARDONI R. (1986) - *Balanced sections and seismic reflection profiles across the central Apennines*. *Mem. Soc. Geol. It.*, **35**, 257-310.
- BIGI G., CASTELLARIN A., CATALANO R., COLI M., COSENTINO D., DAL PIAZ G.V., LENTINI F., PAROTTO M., PATACCA E., PRATURON A., SALVINI F., SARTORI R., SCANDONE P. & VAI G.B. (1989) - *Synthetic structural-kinematic map of Italy, scale 1:2.000.000*. CNR, *Prog. Fin. Geodin.*, Roma.
- BOCCALETTI M., CIARANFI N., COSENTINO D., DEIANA G., GELATI R., LENTINI F., MASSARI F., MORATTI G., PESCATORE T., RICCI LUCCHI F. & TORTORICI L. (1990) - *Palinspastic restoration and paleogeographic reconstruction of the peri-Tyrrhenian area during the Neogene*. *Paleocl., Paleoc., Paleogeog.*, **77**, 41-50.
- BOENZI F., PALMENTOLA G. & VALDUGA A. (1976) - *Caratteri geomorfologici dell'area del Foglio «Matera»*. *Boll. Soc. Geol. It.*, **95**, 527-566.
- BOENZI F., RADINA B., RICCHETTI G. & VALDUGA A. (1971) - *Note illustrative della Carta Geologica d'Italia, F° 201 «Matera»*. *Serv. Geol. It.*, 1-48.
- BRÜCKNER H. (1980a) - *Marine terrassen in Südtalien. Eine quartärmorphologische studie über das Küstentiefland von Metapont*. *Düsseldorfer Geographische Schriften*, **14**, 1-235.
- BRÜCKNER H. (1980b) - *Flussterrassen und flusstäler im küstentiefland von Metapont (Südtalien) und ihre beziehung zu meeresterrassen*. *Düsseldorfer Geographische Schriften*, **15**, 5-32.
- CALCAGNILE G. & PANZA G.F. (1981) - *The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions*. *Pure Appl. Geophys.*, **119**, 865-879.
- CARISSIMO L., D'AGOSTINO O., LODDO C. & PIERI M. (1963) - *Petroleum exploration by AGIP Mineraria and new geological information in Central and Southern Italy, from the Abruzzi to the Taranto Gulf*. 6th Petrol. Int. Congr. Sect. I, 267-292.
- CASNEDI R. (1988a) - *La Fossa bradanica: origine, sedimentazione e migrazione*. *Mem. Soc. Geol. It.*, **41**, 439-448.
- CASNEDI R. (1988b) - *Subsurface Basin Analysis of Fault-Controlled Turbidite System in Bradano Trough, Southern Adriatic Foredeep, Italy*. *Amer. Assoc. of Petrol. Geol. Bull.*, **72**, 1370-1380.
- CASNEDI R. (1991) - *Hydrocarbon accumulation in turbidites in migrating basins of the southern Adriatic foredeep (Italy)*. In: «Basics Models» Bouma and Carter (eds.), 219-233.
- CASNEDI R., CRESCENTI U. & TONNA M. (1982) - *Evoluzione dell'Avanfossa Adriatica meridionale nel Plio-Pleistocene, sulla base di dati di sottosuolo*. *Mem. Soc. Geol. It.*, **24**, 243-260.
- CIARANFI N., GHISSETTI F., GUIDA M., IACCARINO G., LAMBIASE S., PIERI P., RAPISARDI L., RICCHETTI G., TORRE M., TORTORICI L. & VEZZANI L. (1983) - *Carta Neotettonica dell'Italia meridionale*. *Prog. Fin. Geodin. Pubbl. n° 515*, 1-62.
- CIARANFI N., MAGGIORE M., PIERI P., RAPISARDI L., RICCHETTI G. & WALSH N. (1979) - *Considerazioni sulla neotettonica della Fossa bradanica*. *Prog. Fin. Geodin. Pubbl. n° 251*, 73-95.
- CIARANFI N., PIERI P. & RICCHETTI G. (1988) - *Note alla carta geologica delle Murge*. *Mem. Soc. Geol. It.*, **41**, 449-460.
- CIARANFI N., PIERI P. & RICCHETTI G. (1994) - *Linee di costa e terrazzi marini pleistocenici nelle Murge e nel Salento: implicazioni neotettoniche*. Riassunti 77° Congr. Soc. Geol. It., Bari, 170-172.
- COLANTONI P., ASIOLI A., BORSETTI A.M., CAPOTONDI L. & VERGNAUD-GRAZZINI C. (1989) - *Subsidenza tardo-pleistocenica ed olocenica nel medio Adriatico evidenziata dalla geofisica e da ricostruzioni paleoambientali*. *Mem. Soc. Geol. It.*, **42**, 209-220.
- CONSOLE R., DI GIOVAMBATTISTA R., FAVALI P., PRES-GRAVE B.W. & SMRIGLIO G. (1993) - *Seismicity of the Adriatic microplate*. *Tectonophysics*, **218**, 343-354.

- CORREGGIARI A., ROVERI M. & TRINCARDI F. (1992) - *Regressioni «forzate», regressioni «deposizionali» e fenomeni di instabilità in unità progradazionali tardo-quadernarie (Adriatico centrale)*. Giorn. Geol., **54**, 19-36.
- COSENTINO D. & GLIOZZI E. (1988) - *Considerazioni sulle velocità di sollevamento di depositi eutirreniani dell'Italia meridionale e della Sicilia*. Mem. Soc. Geol. It., **41**, 653-665.
- COTECCHIA V. & MAGRI G. (1967) - *Gli spostamenti delle linee di costa quaternarie del mare Ionio fra Capo Spulico e Taranto*. Geol. appl. e Idrogeol., **2**, 3-28.
- COTECCHIA V., DAI PRA G. & MAGRI G. (1969) - *Oscillazioni tirreniane e oloceniche del livello del mare nel Golfo di Taranto, corredate da datazioni col metodo del radiocarbonio*. Geol. appl. e Idrogeol., **4**, 93-148.
- CREMONINI G., ELMI C. & SELLI R. (1971) - *Note illustrative della Carta Geologica d'Italia alla scala 1:100.000, Foglio 156, S. Marco in Lamis*. Serv. Geol. It., 1-65.
- DAI PRA G. & HEARTY P.J. (1988) - *I livelli marini pleistocenici del Golfo di Taranto. Sintesi geocronostratigrafica e tettonica*. Mem. Soc. Geol. It., **41**, 637-644.
- D'ALESSANDRO A., LOIACONO F. & RICCHETTI G. (1989) - *Note illustrative alla Carta Geomorfica del Salento meridionale (F. 525 «Gallipoli», 526 «Nardò», 527 «Otranto», 536 «Ugento», e 537 «Capo S. Maria di Leuca»)*. Quad. Ric. Centro Studi Geot. Ing., **11**, 207-222.
- D'ARGENIO B. (1974) - *Le piattaforme carbonatiche periadriatiche. Una rassegna di problemi nel quadro geodinamico mesozoico dell'area mediterranea*. Mem. Soc. Geol. It., **13**, 137-159.
- DE ALTERIS G. & AIELLO G. (1993) - *Stratigraphy and tectonics offshore of Puglia (Italy, southern Adriatic Sea)*. Marine Geol., **113**, 233-253.
- DE MARCO A. (1990) - *Rapporti tra geodinamica e sedimentazione nella Fossa Bradanica durante il Pleistocene: testimonianze mineralogiche*. Boll. Soc. Geol. It., **109**, 313-324.
- DE VOOGD B., TRUFFERT C., CHAMOT-ROOKE N., HUCHON P., LALLEMANT S. & LE PICHON X. (1992) - *Two-ship deep seismic soundings in the basins of the Eastern Mediterranean Sea (Pasiphae cruise)*. Geophys. J. Int., **109**, 536-552.
- DOGLIONI C. (1991) - *A proposal of kinematic modelling for W-dipping subductions - Possible applications to the Tyrrhenian-Apennines system*. Terra Nova, **3**, 423-434.
- DOGLIONI C. (1993) - *Geological evidence for a global tectonic polarity*. Jour. Geol. Soc. London, **150**, 991-1002.
- DOGLIONI C. (1994) - *Foredeeps versus subduction zones*. Geology, **22** (3) 271-274.
- DOGLIONI C., MONGELLI F. & PIERI P. (1994) - *The Puglia 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.
- DOULCET A., CAZZOLA C. & MARINELLI S. (1990) - *Il campo di Rospo Mare: un esempio di paleokarst petrolifero*. Mem. Soc. Geol. It., **45**, 783-789.
- FAVALI P., FUNICIELLO R., MATTIETTI G., MELE G. & SALVINI F. (1993) - *An active margin across the Adriatic Sea (Central Mediterranean Sea)*. Tectonophysics, **219**, 109-117.
- FAVALI P., MELE G. & MATTIETTI G. (1990) - *Contribution to the study of the Apulian microplate geodynamics*. Mem. Soc. Geol. It., **44**, 71-80.
- FINETTI I. (1982) - *Structure, stratigraphy and evolution of central Mediterranean*. Boll. Geofis. Teor. Appl., **24**, 247-315.
- FINETTI I., BRICCHI G., DEL BEN A., PIPAN M. & XUAN Z. (1987) - *Geophysical study of the Adria plate*. Mem. Soc. Geol. It., **40**, 335-344.
- FUNICIELLO R., MONTONE P., PAROTTO M., SALVINI F. & TOZZI M. (1991) - *Geodynamic evolution of an intra-orogenic foreland: the Apulia case history (Italy)*. Boll. Soc. Geol. It., **110**, 419-425.
- FUNICIELLO R., MONTONE P., SALVINI F. & TOZZI M. (1988) - *Caratteri strutturali del promontorio del Gargano*. Mem. Soc. Geol. It., **41**, 1235-1243.
- GAMBINI R. & TOZZI M. (1995) - *Geodynamic evolution of the southern Adria microplate*. Terra Abst. Strasbourg, 176-177.
- GUERRICCHIO A. & WASOWSKI J. (1988) - *Some remarks on the tectonic significance of the paleomagnetic data from Gargano, Southern Italy*. Mem. Soc. Geol. It., **41**, 1263-1269.
- HEARTY P.J. & DAI PRA G. (1992) - *The age and stratigraphy of middle Pleistocene and younger deposits along the Gulf of Taranto (Southeast Italy)*. J. Coastal Res., **8** (4), 882-905.
- IANNONE A. & PIERI P. (1979) - *Considerazioni critiche sui tufi calcarei delle Murge. Nuovi dati litostatigrafici e paleoambientali*. Geogr. Fis. Din. Quat., **2**, 173-186.
- IANNONE A. & PIERI P. (1982) - *Caratteri neotettonici delle Murge*. Geol. Appl. e Idrog., **17**, 147-159.
- KRUSE S.E. & ROYDEN L.H. (1994) - *Bending and unbending of an elastic lithosphere: The Cenozoic history of the Apennine and Dinaride foredeep basins*. Tectonics, **13** (2), 278-302.
- LOIACONO F. & SABATO L. (1987) - *Stratigrafia e sedimentologia di depositi Pleistocenici di fan-delta sul margine appenninico della Fossa Bradanica*. Mem. Soc. Geol. It., **38**, 275-296.
- MALINVERNO A. & RYAN W.B.F. (1986) - *Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere*. Tectonics, **5**, 227-245.
- MONGELLI F. (1975) - *Aspetti geodinamici della piastra apula. Considerazioni sui dati gravimetrici e sismologici*. Paper presented at Seminario sulla piattaforma carbonatica apula, University of Bari, March 6-7.
- MONGELLI F., LODDO M. & CALCAGNILE G. (1975) - *Some observations on the Apennines gravity field*. Earth Planet. Sci. Lett., **24**, 385-393.
- MONGELLI F., MAROTTA A. & DOGLIONI C. (1994) - *Differenti tipi di litosfera e differenti stili di subduzione della placca adriatica*. Atti del 13° convegno del NGTGS, 28-30 novembre, Roma, 13-24.

- MONGELLI F., ZITO G., DELLA VEDOVA B., PELLIS G., SQUARCI P. & TAFFI L. (1991) - *Geothermal Regime of Italy and surrounding Seas*. In: Exploration of the deep continental crust, Springer-Verlag Berlin, 381-394.
- MOSTARDINI F. & MERLINI S. (1986) - *Appennino centro-meridionale. Sezioni geologiche e proposta di modello strutturale*. Mem. Soc. Geol. It., **35**, 177-202.
- NICOLICH R. (1989) - *Crustal structures from seismic studies in the frame of the European Geotraverse (southern segment) and Crop projects*. In «The lithosphere in Italy» edited by A. Boriani, M. Bonafede, G.B. Piccardo, and G.B. Vai, Accad. Naz. Lincei, **80**, 41-61.
- ORI G.G., SERAFINI G., VISENTIN C., RICCI LUCCHI F., CASNEDI R., COLALONGO M.L. & MOSNA S. (1991) - *The Pliocene-Pleistocene Adriatic Foredeep (Marche and Abruzzo, Italy): an integrated approach to surface and subsurface geology*. 3rd E.A.P.G. Conference, Florence, Adriatic Foredeep Field Trip Guide Book, 1-85.
- PACCHIAROTTI E. (1982) - *Exploration effort in the Italian offshore, in Oil Activities Offshore*. Italian-Norwegian Seminar, 27-28 October, Milano.
- PAREA G.C. (1986) - *I terrazzi marini tardo-pleistocenici del fronte della catena appenninica in relazione alla geologia dell'avanfossa adriatica*. Mem. Soc. Geol. It., **35**, 913-936.
- PIERI P. (1980) - *Principali caratteri geologici e morfologici delle Murge*. Murgia sotterranea, Boll. Gruppo Speleo Martinense, **2** (2), 13-19.
- PIERI P., SABATO L. & TROPEANO M. (1994) - *Evoluzione tettonico-sedimentaria della Fossa bradanica a sud dell'Ofanto nel Pleistocene*. In: Guida alle escursioni. Congr. Soc. Geol. It. Bari. Quaderni Bibl. Prov. Matera, **15**, 35-54.
- RICCHETTI G. (1967) - *Osservazioni preliminari sulla geologia e morfologia dei depositi quaternari nei dintorni del Mar Piccolo (Taranto)*. Atti Acc. Gioenia di Sc.Nat. in Catania, s. 6, **18**, 123-130.
- RICCHETTI G. (1972) - *Osservazioni geologiche e morfologiche preliminari sui depositi quaternari affioranti nel F° 203 «Brindisi»*. Boll. Soc. Nat. in Napoli, **81**, 543-566.
- RICCHETTI G. (1980) - *Contributo alla conoscenza strutturale della Fossa bradanica e delle Murge*. Boll. Soc. Geol. It., **99**, 421-430.
- RICCHETTI G. & MONGELLI F. (1980) - *Flessione e campo gravimetrico della micropiastra apula*. Boll. Soc. Geol. It., **99**, 431-436.
- RICCHETTI G., CIARANFI N., LUPERTO SINNI E., MONGELLI F. & P. PIERI (1988) - *Geodinamica ed evoluzione sedimentaria e tettonica dell'avampaese apulo*. Mem. Soc. Geol. It., **41**, 57-82.
- ROYDEN L., PATACCA E. & SCANDONE P. (1987) - *Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution*. Geology, **15**, 714-717.
- SCHWANDER M.M. (1989) - *The Southern Adriatic Basin, offshore Italy*. In «Atlas of Seismic Stratigraphy», edited by A.W. Bally, Amer. Ass. Petrol. Geol., Studies in Geology, **27** (3), 112-115.
- SELLA M., TURCI C. & RIVA A. (1988) - *Sintesi geopetroliera della Fossa Bradanica*. Mem. Soc. Geol. It., **41**, 87-108.
- SELLI R. (1962) - *Le Quaternaire marin du versant Adriatique-Ionien de la péninsule italienne*. Quaternaria, **6**, 391-413.
- TRAMUTOLI M., PESCATORE T., SENATORE M.R. & MIRABILE L. (1984) - *Interpretation of reflection high resolution seismic profiles through the Gulf of Taranto (Ionian sea, Eastern Mediterranean)*. The structure of Apennine and Apulia deposits. Boll. Ocean. Teor. Appl., **2** (1), 33-52.
- TROPEANO M., MARINO M. & PIERI P. (1994) - *Evidenze di tettonica distensiva plio-pleistocenica al margine orientale della fossa bradanica: l'horst di Zagarella*. Il Quaternario, **7** (2), 597-606.
- VEZZANI L. (1967) - *I depositi plio-pleistocenici del litorale ionico della Lucania*. Atti Acc. Gioenia di Scienze Nat. in Catania, s. 6, **18**, 159-180.
- VILLA I.M. (1985) - *Cronologia ³⁹Ar/⁴⁰Ar del Complesso Vulcanico del Monte Vulture*. Rend. SIMP, **41**, 146-147.
- ZAPPATERRA E. (1994) - *Source-rock distribution model of the Periadriatic region*. Amer. Assoc. Petroleum. Geol. Bull., **78** (3), 333-354.