Tectonics and Seismicity of the Apulian Ridge south of Salento Peninsula (Southern Italy)

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Tectonics and seismicity of the Apulian Ridge south of Salento peninsula (Southern Italy)

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Abstract
Multichannel reflection seismic data were acquired south of the Salento peninsula, in an area where crustal seismicity has been recorded. Seismic profiles show the presence of small grabens bounded by extensional faults with NW-SE direction. These grabens are filled with Plio-Quaternary sediments and represent the prolongation of the grabens located onshore in the Salento peninsula. Outer arc extension due to flexuring of the Adriatic-Apulian lithosphere under the double load of the Hellenides and Apennines-Calabrian arc is thought to have originated these grabens. The Adriatic-Apulian continental lithosphere presents a very small radius of curvature and a decoupling between upper crust and mantle lithosphere is expected. Inner arc compression within the upper crust may be responsible for the seismicity recorded in the area.

Key words *tectonics – seismicity – multichannel seismic reflection – Apulia – lithosphere flexure*

1. Introduction

The position of Adria with respect to the African plate has been a long debated issue in the geological literature concerning the Mediterranean geology. Some Authors favoured Adria as a separate microplate (*e.g.*, Anderson and Jackson, 1987; Console *et al.*, 1989; Westaway, 1990; Favali *et al.*, 1990; Console *et al.*, 1993), whereas others considered it a promontory of Africa (*e.g.*, McKenzie, 1972; Channell *et al.*, 1979; Lowrie, 1986; Channell, 1996; Mele, 2001). As far as neotectonics is concerned, several crustal earthquakes have been recorded south of the Salento peninsula (fig. 1). These earthquakes are not easily linked to the major tectonic features of the area and have been taken as possible evidence for an incipient decoupling between Adria and Africa (Anderson and Jackson, 1987). However, geological evidence supporting the presence of a plate boundary south of Salento is lacking. Based on recently acquired multichannel reflection seismic profiles this paper aims to present an alternative interpretation to account for the seismic activity recorded south of the Salento peninsula. In particular, a local stress accumulation due to the small radius of curvature of the Adriatic-Apulian plate under the double load of the Hellenides and Apennines-Calabrian arc, is proposed to be the main triggering factor.

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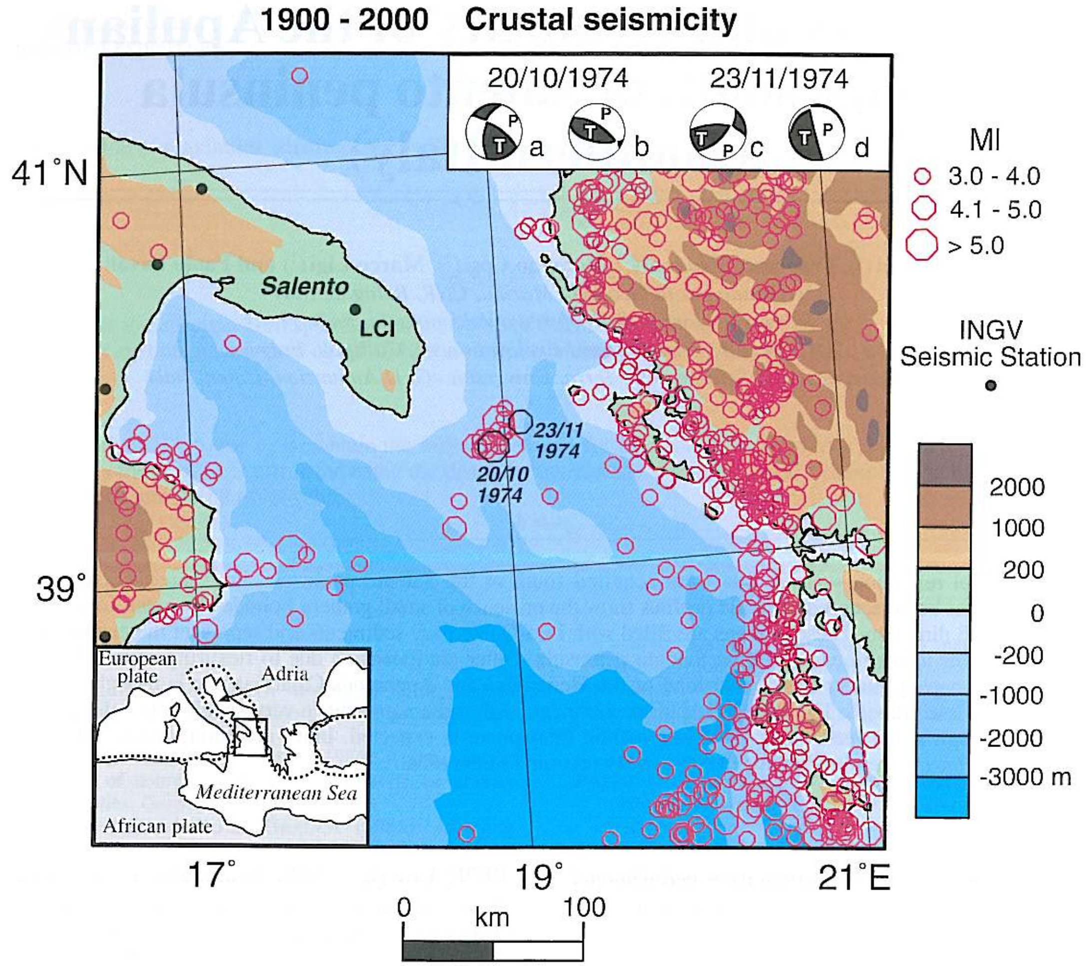

Fig. 1. Bathymetry and topography of the study area and surrounding regions with the epicentral distribution of $M_l \geq 3.0$ seismicity recorded from 1900 to 2000. Lower left inset shows location of the study area. Upper right inset shows the focal mechanisms obtained for the 20th October 1974 event (a: Favali *et al.*, 1990; b: D'Ingeo *et al.*, 1980) and the 23rd November 1974 event (c: D'Ingeo *et al.*, 1980; d: Gasparini *et al.*, 1985). *P* and *T* axes are also indicated.

2. Geological setting

The Apulian Ridge (AR) is a morphological element that separates the deep Ionian basin from the shallower Southern Adriatic basin, extending from the southern tip of Puglia (Salento peninsula) to the island of Kefallinia, becoming progressively deeper (fig. 2).

Geological and geophysical data (Channell *et al.* 1979; Auroux *et al.*, 1984; Mascle *et al.*, 1984; Ricchetti *et al.*, 1988; Scarascia *et al.*, 1994) indicate that the AR is made up of a thick sedimentary succession underlain by continental crust. Mesozoic shallow-water carbonates are widely outcropping in Puglia (Ricchetti *et al.*, 1988) and have also been sampled along

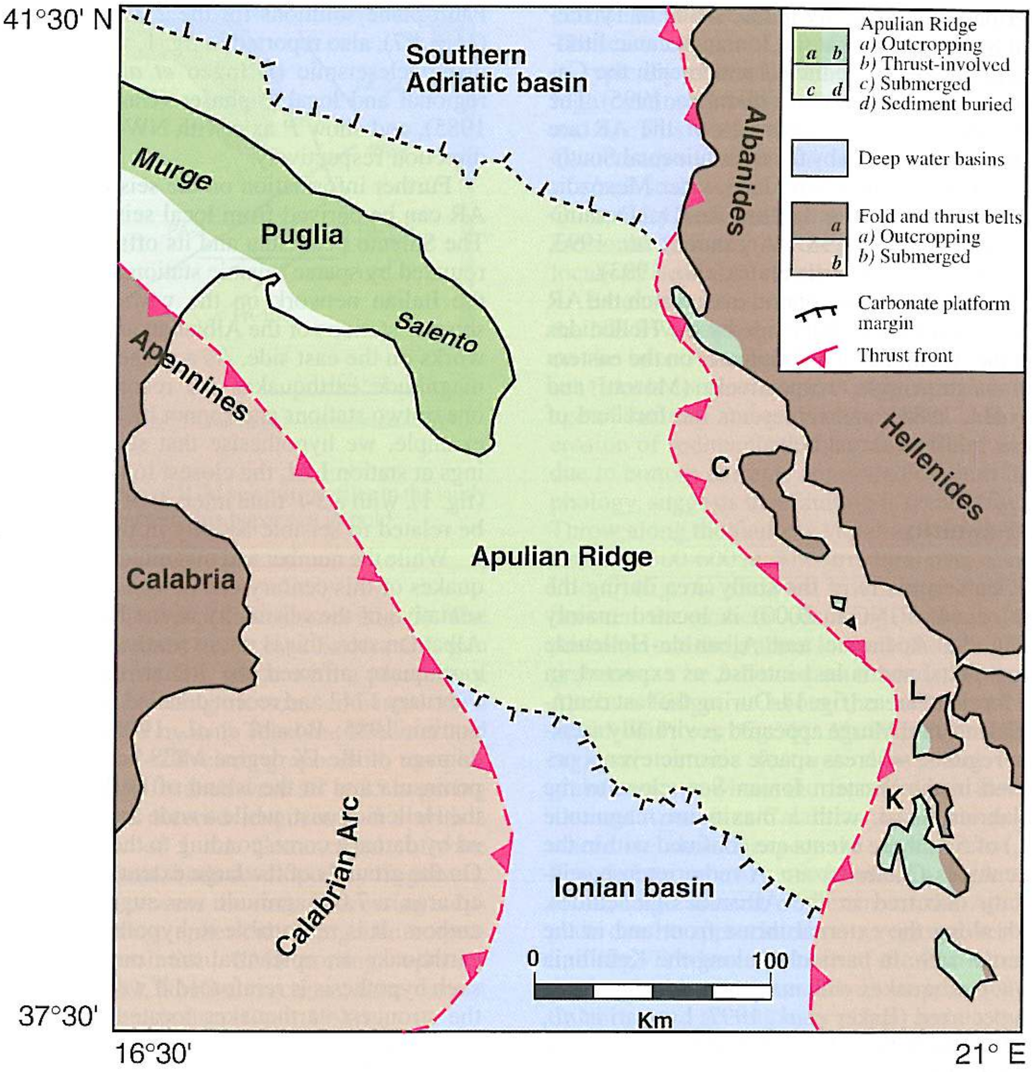

Fig. 2. Geological setting of the study area. The Apulian Ridge represents the foreland of the Apennines and Hellenides fold-and-thust belts. In the northern and southern parts of the Apulian Ridge the original margins of the Mesozoic carbonate platform are still preserved, passing to the deeper water Southern Adriatic and Ionian basins, respectively. K = Kefallinia island; L = Lefkas island, C = Corfu island.

the southern escarpment of the AR (Biju-Duval *et al.*, 1982). The southern margin of the AR faces the deep-water Ionian basin which is floored by oceanic crust as indicated by Expanded Spreading Profile experiments (de Voogd *et al.*, 1992). The thick sedimentary cover of the Ionian basin has not been drilled and the age of the oceanic basement is debated; interpretations range from Permo-Triassic (Stampfli *et al.*, 1991) to Cretaceous (Dercourt *et al.*, 1993). Deep and intermediate seismicity in the Southern Tyrrhenian Sea suggests that the Ionian oceanic lithosphere has been subducted underneath the Calabrian arc (Selvaggi and Chiarabba, 1995). The Mesozoic platform carbonates of the AR are bounded to the north by the epicontinental Southern Adriatic basin where deep water Mesozoic facies deposited since the Jurassic (De' Dominicis and Mazzoldi, 1987; Argnani *et al.*, 1993, 1994, 1996; De Alteriis and Aiello, 1993).

The Adriatic lithosphere, over which the AR rests, is loaded on either side by the Hellenides and the Apennines-Calabrian arc, on the eastern and western side, respectively (Moretti and Royden, 1988), and represents the foreland of these fold-and-thrust belts.

3. Seismicity

The seismicity of the study area during the last century (INGV, 2000) is located mainly along the Apennine and Albanide-Hellenide thrust belts, and is less intense, as expected, in the foreland areas (fig. 1). During the last century Salento and Murge appeared as virtually aseismic regions, whereas sparse seismic events occurred in the Western Ionian Sea, close to the Calabrian coast, with a maximum magnitude (M_l) of 5.4; these events are confined within the Apennines-Calabrian arc. A more intense seismicity occurred in the Albanides-Hellenides, both along the external thrust front and in the internal area. In particular, along the Kefallinia fault, earthquakes with maximum M_S magnitude 7.3 occurred (Baker *et al.*, 1997; Louvari *et al.*, 1999), where the AR is overridden by a major lateral ramp of the Hellenide thrust belt (Argnani *et al.*, 1998). The foreland region south-east of the Salento peninsula did not show a significant seismicity in the period 1900-2000; crustal seismic sequences of moderate magnitude occurred only between 1974 and 1977 and in 1991. For the strongest event (20/10/1974, $M_l = 5.1$), the focal mechanism was determined by D'Ingeo *et al.* (1980) and Favali *et al.* (1990) using teleseismic waves. The two mechanisms show a different fault plane solution, but have a similar direction of the P axis, ranging from NE-SW to ENE-WSW (see inset of fig. 1). Fault-plane solutions for the 23/11/1974 event ($M_l = 4.7$), also reported in fig. 1, were obtained using teleseismic (D'Ingeo *et al.*, 1980) and regional and local P phases (Gasparini *et al.*, 1985), and show P axis with NW-SE and E-W direction respectively.

Further information on the seismicity of the AR can be derived from local seismic records. The Salento peninsula and its offshore are surrounded by sparse seismic stations belonging to the Italian network on the west side and by seismic stations of the Albanian and Greek networks on the east side. As a consequence, low-magnitude earthquakes are recorded only by one or two stations and cannot be localized. For example, we hypothesise that seismic recordings at station LCI, the closest to the study area (fig. 1), with a S-P time interval of 5-15 s, might be related to seismic activity in the AR.

While the number and magnitude of the earthquakes of this century can be considered representative of the seismicity of the Hellenide and Albanian area, this is not so for the AR. A strong earthquake affected the Ionian region on 20 February 1743 and recent detailed studies (Margottini, 1985; Boschi *et al.*, 1995) recognised damage of the IX degree MCS both in Salento peninsula and in the island of Lefkas, close to the Hellenic coast, while a wide area was affected by damage corresponding to the VIII degree. On the grounds of the large extent of the affected area, a 7.0 magnitude was suggested by the authors. It is reasonable to hypothesise for this earthquake an epicentral area on the AR and such hypothesis is reinforced if we consider that the strongest earthquakes located close to the island of Kefallinia (*e.g.*, 12/8/1953 I_0 = XI MCS and $M_S = 7.3$) are felt with effects of V-VI MCS in Salento. The occurrence of strong earthquakes within the study area is also suggested by Pieri *et al.* (1997), considering the sparse occurrence of seismites in the Tyrrhenian deposits along the Adriatic-Apulian coast.

4. Seismic reflection data – description and interpretation

Multichannel reflection seismic profiles were collected during two surveys carried out in 1991

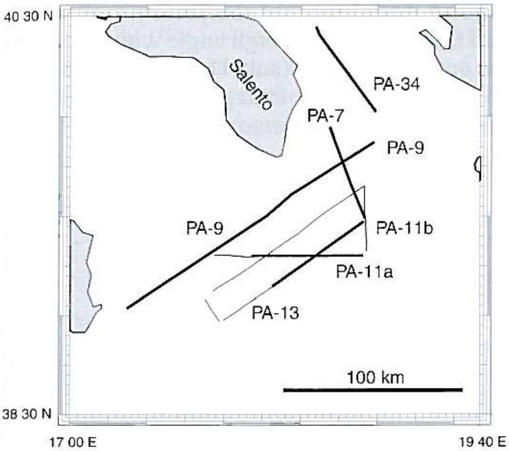

Fig. 3. Location of IGM seismic profiles in the study area. Lines shown in this paper are in bold.

and 1994 on board of R/V Urania (fig. 3). The seismic source was given by a Sodera G.I. gun operating in true G.I. mode with a pressure of 2000 psi. Recording devices consisted of a 24-channel 600 m-long Teledyne streamer and a Geometrics 2420 seismograph. Both trace interval and shot distance were set at 25 m giving a 1200% fold. Record length was 5 s with a sampling rate of 1 ms. Commercial software Disco and Focus, both developed by Cogniseis, were used to process the data. Processing steps included editing, spherical divergence corrections, deconvolution, CMP sorting, velocity analysis, DMO, NMO corrections, time-variant filtering and migration (Cosi, 1996).

In addition, industrial multichannel reflection seismic profiles, belonging to commercial zones «D» and «F», and well data were made available by the Ministry of Industry. Although these data were used in the interpretation they will not be shown or described.

The reflector marking the base of the Plio-Quaternary sedimentary succession is well recognisable on seismic profiles. This reflector represents a boundary between relatively deep-water clastic sediments, typically fine grained, on top and shallow-water sediments, mainly carbonates, below. The latter are often Cretaceous shallow-water carbonates as indicated by commercial wells in the Salento offshore (Cosi, 1996). The seismic facies of Plio-Quaternary sediments is typically characterised by high amplitude, high continuity subparallel reflections (figs. 4 and 5). This well defined layering of the Plio-Quaternary sediments favours the identification of small scale faults. The upper part of the Plio-Quaternary sedimentary package shows often erosional features on the sea floor, typically localised near small fault scarps (fig. 5).

Extensional faults and grabens are shown on the NE-SW-trending profiles (figs. 4 and 5) and on the base Plio-Quaternary map (fig. 6). The sea floor is commonly offset suggesting a recent age of faulting and graben formation. Also the erosion of sediments at the graben floor, likely due to bottom currents controlled by fault morphology, suggests that faulting is recent (fig. 5). Throw along the faults is variable, but typically less than 500-600 m. The structural map of base Plio-Q (fig. 6) shows a continuity of trends between the grabens occurring in the Salento peninsula and the grabens located offshore. These grabens can be followed southwards, along the Apulian Ridge, at about the latitude of the island of Paxos (fig. 6). An inspection of the regional tectonic features shows that these grabens occur where the fronts of the Hellenides and Apennines-Calabrian arc are closer, *i.e.* where we should expect the curvature of the flexed plate to be at a maximum (fig. 1). A view of the large amount of flexure of the Apulian plate can be appreciated on a regional seismic line (fig. 7) where the base of the Plio-Quaternary reflector dips westwards underneath the Calabrian arc accretionary prism, and eastward towards the Hellenides .

5. Discussion and conclusions

Reflection seismic profiles show the presence of small grabens bounded by extensional faults of limited throw with NW-SE direction. These grabens are filled with Plio-Quaternary sediments and represent the prolongation of the grabens located onshore in the Salento peninsula. Altogether, the narrow belt affected by limited extension stretches for about 150 km along the axis of the AR (fig. 6).

It has been argued that the grabens characterising the Salento Peninsula can be related to fault-block rotation around vertical axes within a strike-slip tectonic regime (Tozzi *et al.*, 1988; Tozzi, 1993; Gambini and Tozzi, 1996). This kind of model requires the presence of strike-slip faults trending at high angle with respect to the graben boundary faults (McKenzie and Jackson, 1983; Jackson, 1991) and, in fact, the occurrence offshore Salento of dextral E-W-trend-

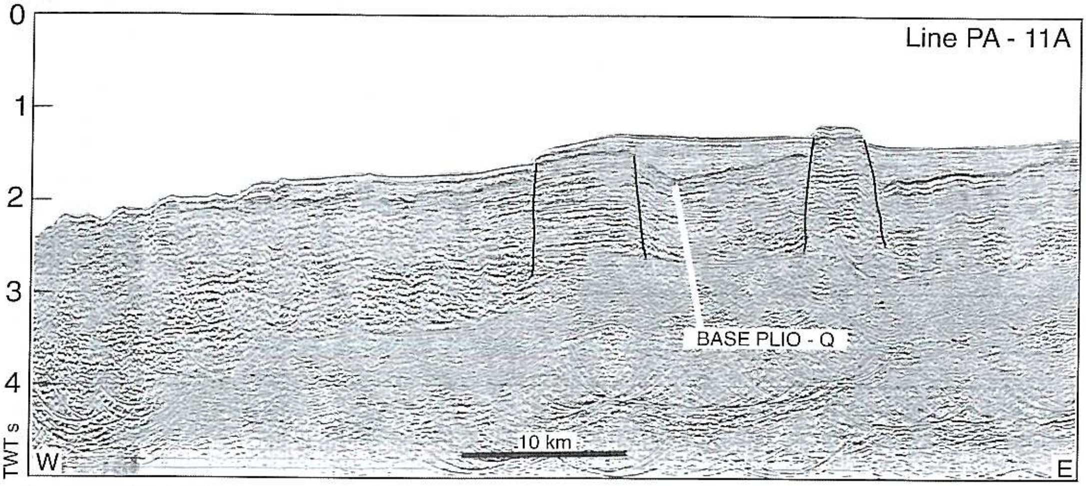

Fig. 4. Seismic profile PA-11A illustrating the geometry of the high angle extensional faults offsetting the base Plio-Quaternary reflection. Note the limited fault throws.

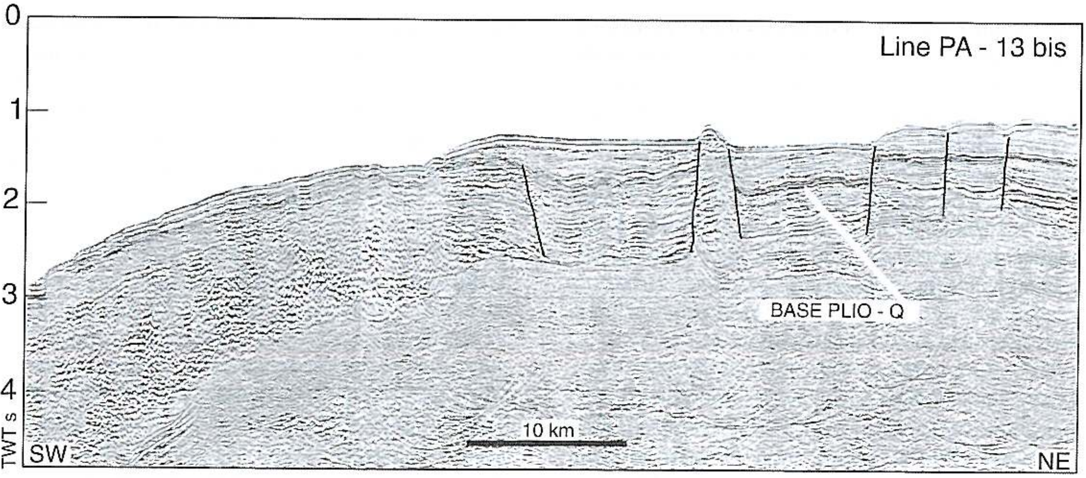

Fig. 5. Seismic profile PA-13bis. High angle extensional faults displace the base Plio-Quaternary reflection. A small graben is visible in the right half of the line. Growth strata are absent within the graben, whereas pre-faulting Plio-Quaternary sediments within the graben are eroded near the graben's shoulders.

ing strike-slip faults has been proposed (Gambini and Tozzi, 1996). However, we could not find evidence of such faults on our survey (fig. 6) as seismic lines running parallel to the graben faults (figs. 8 and 9) fail to show any significant E-W-oriented discontinuity. Furthermore, the preliminary paleomagnetic data supporting rotation about vertical axes (Tozzi *et al.*, 1988) do not stand more sophisticated statistical tests (Bazhenov and Shipunov, 1991).

The lack of E-W-trending strike-slip faults and the continuity trend of extensional faults suggest that the grabens did not originate from block rotation about vertical axes, as previously suggested. Instead, the spatial coincidence between maximum flexural curvature of the Adriatic plate (fig. 10) and grabens occurrence indicates a possible relationship between the two observables. In this case, the grabens may have

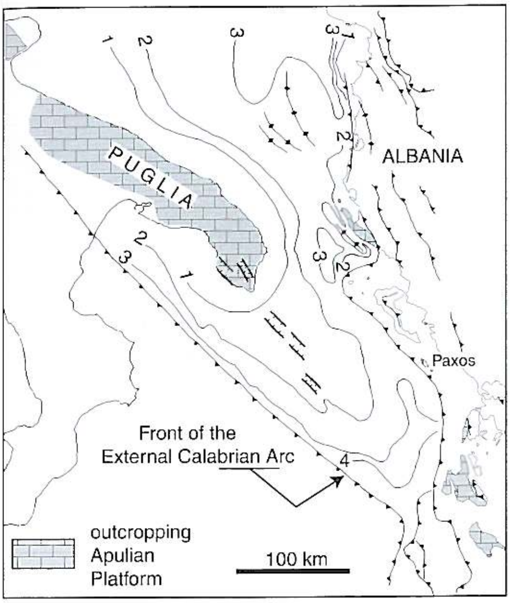

Fig. 6. Structural map of the base of Plio-Quaternary sediments with location of the major extensional faults (ticked lines) in the Apulian Ridge. It is worth noting the continuity of direction with the faults mapped on land in the Salento peninsula. Barbed lines represent the Calabrian arc and Hellenide thrust fronts. Lines with diamonds indicate fold axes and the outcrops of Apulian platform units are shown in brick pattern. Note that the external front of the Calabrian arc is drawn here more accurately with respect to fig. 2, on the basis of a recent seismic reflection survey (Argnani *et al.*, 1998).

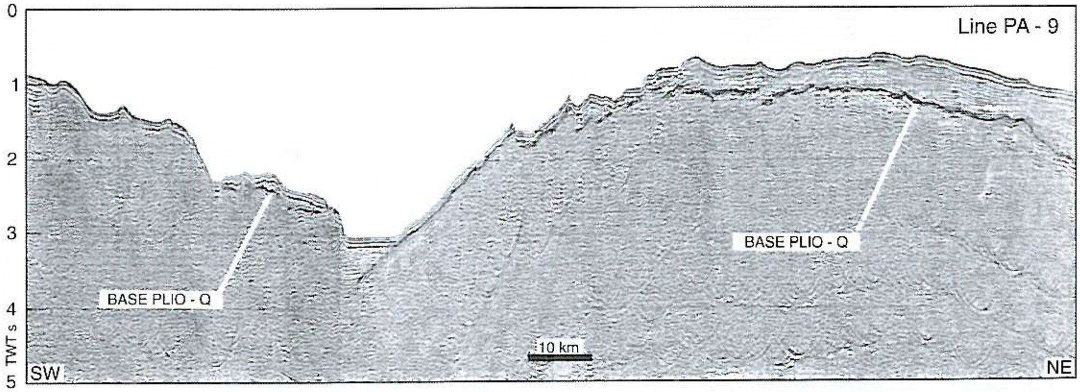

Fig. 7. Seismic profile PA-9 showing the strong curvature of the Apulian plate, described by the base Plio-Quaternary reflection surface which dips westwards underneath the Calabrian arc accretionary prism, and eastward towards the Hellenides. Extensional faults affecting the generally thin Plio-Quaternary sedimentary cover can be identified by the offset base of Plio-Quaternary. Note that the thickness of Plio-Quaternary sediments increases eastwards, towards the Hellenides thrust front.

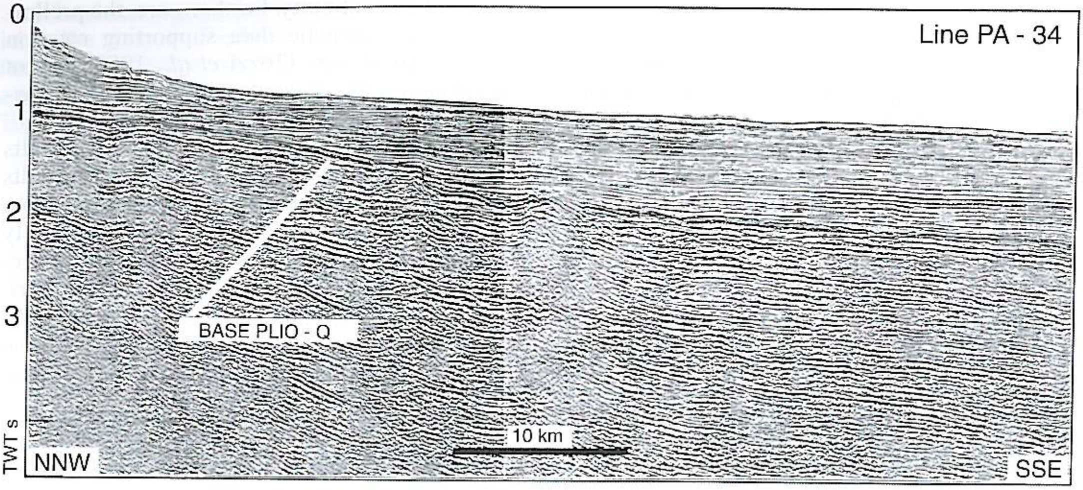

Fig. 8. Seismic profile PA-34. This line runs roughly perpendicular to the inferred extensional direction and shows the absence of E-W-trending strike-slip faults within the Plio-Quaternary sediments which appear undisturbed. The distal part of the Salento prograding wedge is present in the north-western end of the line.

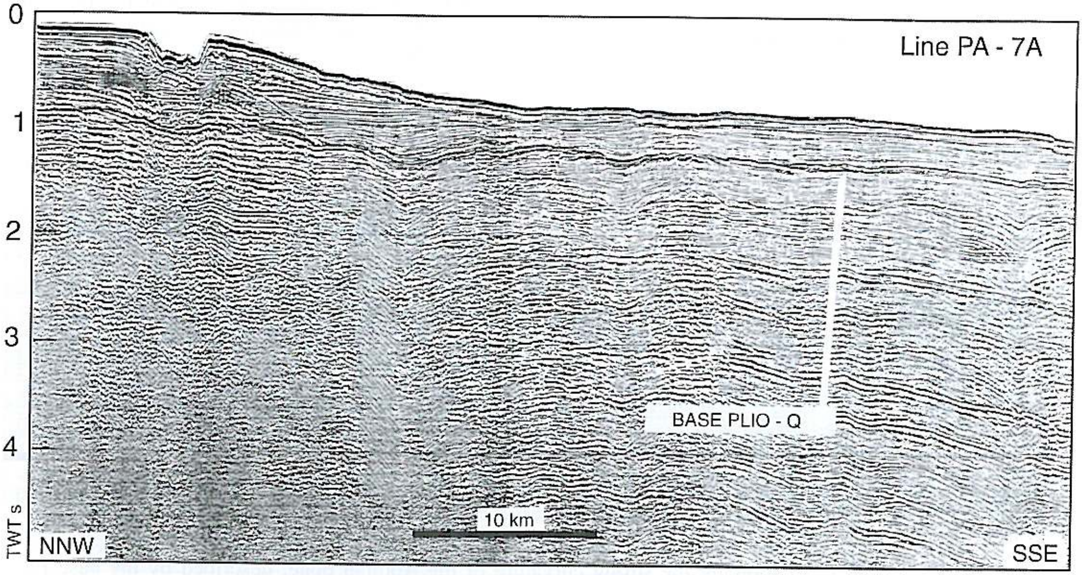

Fig. 9. Seismic profile PA-7A roughly perpendicular to the inferred extensional direction. As in line PA-34, no E-W-trending strike-slip faults affect the Plio-Quaternary sediments. The Salento prograding wedge, on the north-western part of the line, is cut by an erosional feature.

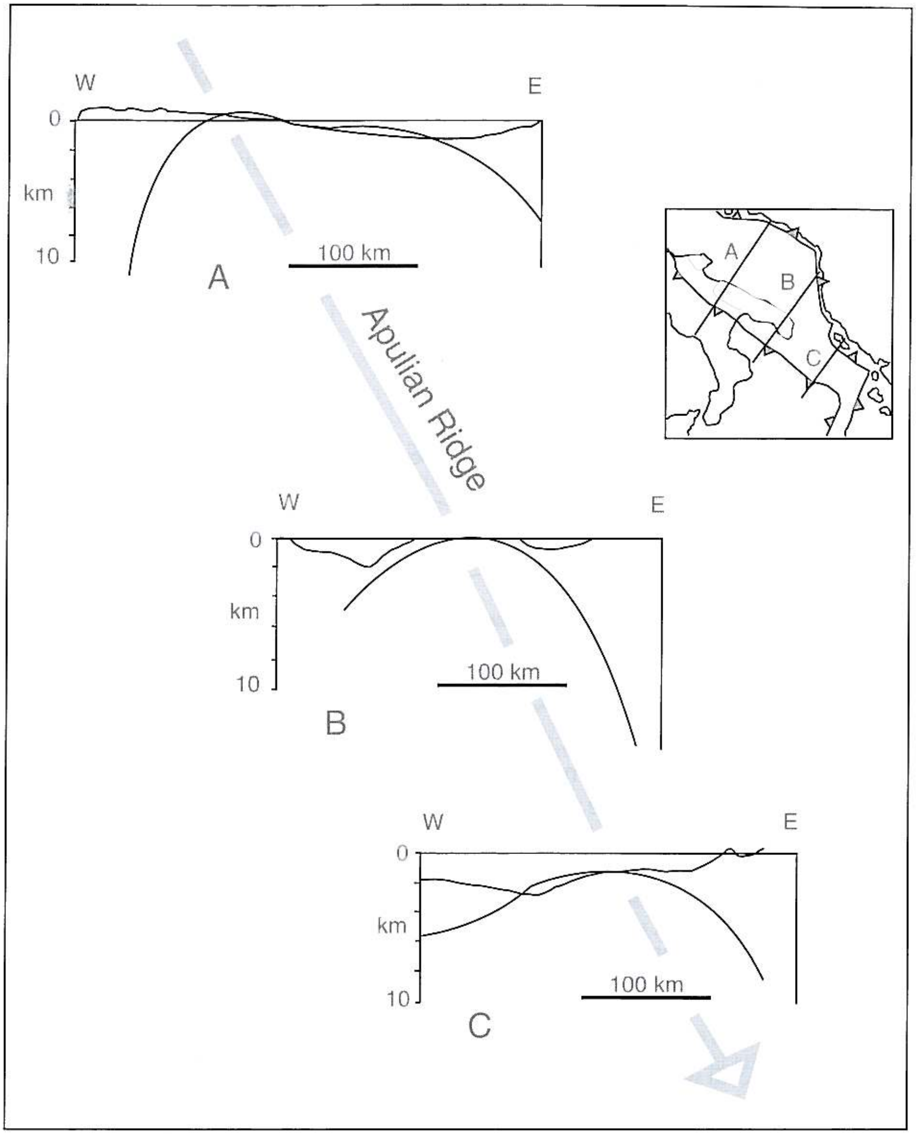

Fig. 10. Curvature of the Apulian plate derived from inversion of gravity anomaly data along three transects (after Moretti and Royden, 1988). The area affected by extensional tectonics coincides with the sector of maximum curvature (section B).

originated by outer-arc extension (Bradley and Kidd, 1991; fig. 11a) during flexure of the Adriatic plate. It is worth noting that the flexure of the Adriatic plate is a relatively young feature as thrust activity during the Plio-Pleistocene, to reach the present loading configuration, has been reported for both the Hellenides and Southern Apennines (Marsella *et al.*, 1995; Argnani *et al.*, 1996; Menardi-Noguera and Rea, 2000). Within age uncertainties, extension in the grabens

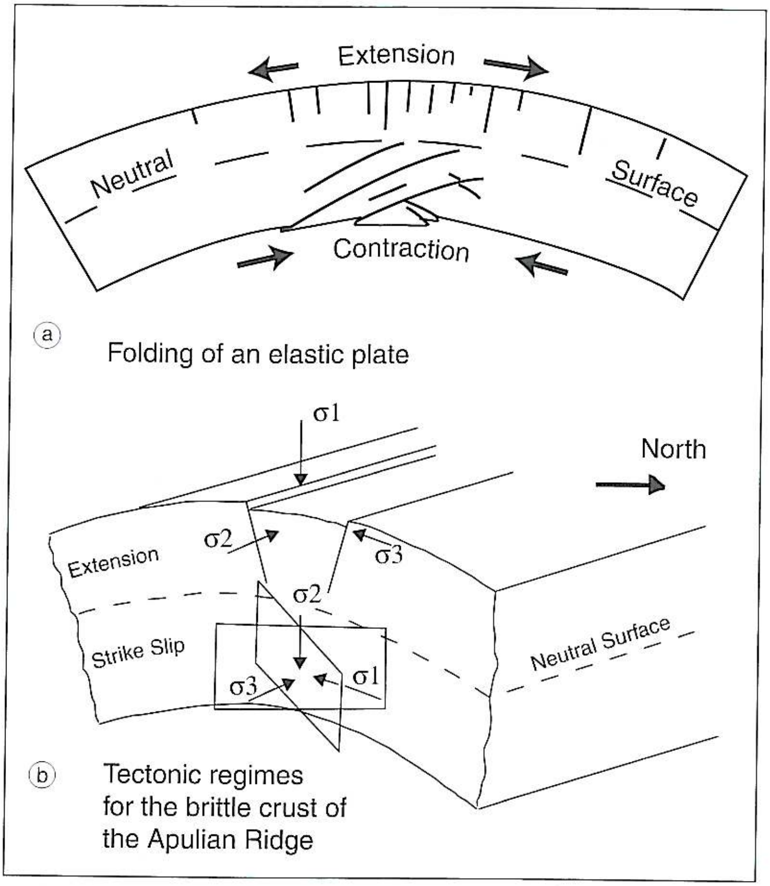

Fig. 11a,b. a) Outer arc extension and inner arc contraction originated by folding of an elastic plate. The two opposite tectonic regimes are separated by a neutral surface. b) Types and orientation of faults according to the model proposed for the Apulian Ridge tectonics (after Price and Cosgrove, 1990).

seems to be roughly coeval with the recent plate flexuring.

The Equivalent Elastic Thickness (EET) offers a way to estimate the lithospheric strength in response to loading (Burov and Diament, 1995). For a realistic continental lithosphere (Kirby and Kronenberg, 1987) the EET is strongly affected by the flexural stresses caused by bending (Burov and Diament, 1995, 1996). The lower the radius of curvature of a given lithosphere is, the lower the EET. With increasing stress, *i.e.* increasing plate curvature, the lower crustal material can undergo ductile failure and a decoupling between upper crust and mantle lithosphere can occur. When the radius of curvature is particularly small (less than 1000 km) a realistic continental lithosphere is very likely in a decoupling mode (fig. 12a). The radius of curvature of the Adriatic lithosphere in the area of the AR south of Salento is very small, in the order of 600 km (Moretti and Royden, 1988), and decoupling between upper crust and lithospheric mantle should be expected (fig. 12a). In this case, the upper crust can fold independently, with its own neutral surface, giving rise to inner arc contraction (fig. 12b). Furthermore, in the real world the deformation of the flexed lithosphere is not perfectly elastic, as extensional faults at surface and earthquakes at depth are commonly encountered (Chappel and Forsyth, 1979).

The sparse seismicity that characterises the AR south of the Salento peninsula is typical of intraplate activity, taking into account the low number of earthquakes, particularly when compared to the activity of the nearby Apennines and Albanides-Hellenides (fig. 1). On the other hand, this seismic activity can be considered a direct consequence of the compressional stresses acting in the two surrounding thrust belts. Magnitudes are typically low and only in a few cases have focal mechanisms been obtained (D'Ingeo *et al.*, 1980; Gasparini *et al.*, 1985;

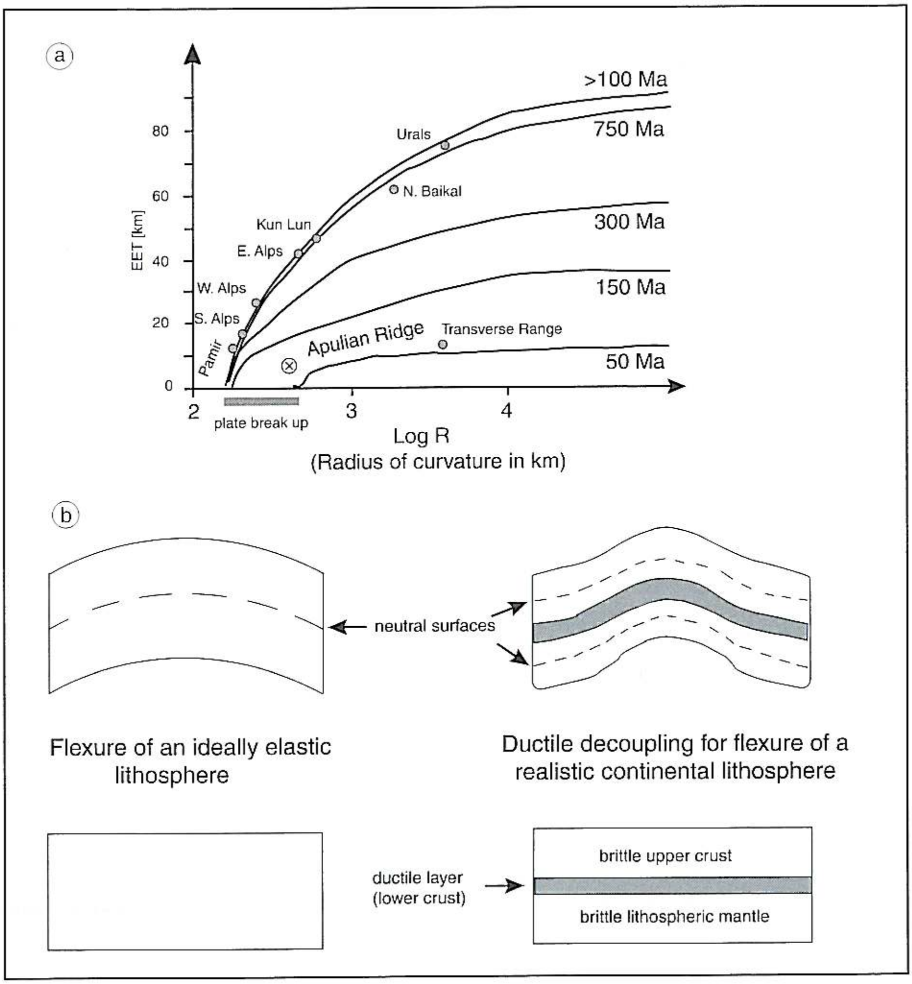

Fig. 12a,b. a) Plot of EET (Effective Elastic Thickness) *versus* radius of curvature (after Burov and Diament, 1995, 1996). The Apulian plate falls in the field of plate break up. A decoupling between upper crust and upper mantle is therefore expected. b) Comparison of flexural behaviour between a pristine ideally elastic lithosphere and a realistic continental lithosphere subject to decoupling. The position of a neutral surface in the upper crust of the decoupled lithosphere allows inner arc compression at relatively shallow depth.

Favali *et al.*, 1990). The focal solution of Favali *et al.* (1990) shows a strike-slip mechanism with a *P* axis oriented roughly NE-SW and with slip planes oriented NW-SE and NNE-SSW, sinistral and dextral, respectively (fig. 1). This seismicity has been taken as possible evidence for an incipient plate boundary between Adria and Africa (D'Ingeo *et al.*, 1980; Anderson and Jackson, 1987). Note that although a strike-slip tectonic regime in the region has been inferred from geological evidence (Tozzi, 1993; Gambini and Tozzi, 1996), the proposed E-W-trending dextral strike-slip faults do not match the earthquake focal mechanism solution (Favali *et al.*, 1990) which gives a dextral strike-slip motion along a fault plane with NNE-SSW direction. Within the geodynamic framework outlined above, we propose an alternative explanation for this seismic activity and the reported focal mechanisms. The inner arc contraction due to decoupled bending of the upper crust may be responsible for the NE-SW oriented *P* axis which, in fact, is almost perpendicular to the axial trend of the AR. The hypocentral depth of the 20th October 1974 event has not been determined and this earthquake has been generically indicated as crustal. Within intraplate earthquakes the larger events tend to cluster at the base of the brittle layer (Scholz, 1989); it appears therefore reasonable to have the 20th October 1974 event at a depth of 10-15 km or more, and locate at this depth (or deeper) also the 1743 earthquake. In the outer arc of the folded lithosphere, above the neutral surface, extensional grabens with faults trending parallel to the bending axis are present. This suggests that the vertical stress coincides with $\sigma 1$ and that $\sigma 2$ is parallel to the flexural fold axis (fig. 11b). It seems therefore likely that at greater depth, below the neutral surface, where earthquakes with horizontal *P* axes occur, the vertical stress coincides with $\sigma 2$. In this region, the stress ellipse describes a strike slip regime instead of a compressional one (fig. 11b) and is consistent with the calculated focal mechanism.

To sum up, the origin of the Apulian Ridge grabens can be reasonably explained by the flexuring of the Adriatic-Apulian lithosphere under the double load of the Hellenide and Apennine-Calabrian arc fold-and-thrust belts. This low-radius flexuring could also be responsible for the moderate seismicity observed in the area as it should induce a decoupling between the upper and lower lithosphere, allowing inner arc compression at relatively shallow crustal level. Given the very low radius of curvature, outer arc extensional stresses are likely very large and we should consider the observed throws on extensional faults as close to the maximum. In fact, in the adjacent parts of the AR, to the north and to the south of the extensional grabens, where curvature has larger radius (fig. 10), there is no sign of comparable extensional tectonics, suggesting that stresses are not large enough to break the rocks.

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