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Present-day stress field and active tectonics in southern peninsular Italy

Alessandro Amato and Paola Montone
Istituto Nazionale di Geofisica, Via di Vigna Murata 605, 00143 *Rome, Italy*

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SUMMARY

A systematic collection of present-day stress directions has allowed us to gain new insights into the recent tectonic evolution of the Italian Peninsula. Horizontal stress directions from breakouts in 40 deep wells drilled for oil exploration have been compared to compressional and tensional axes of 17 earthquake fault-plane solutions ($4.2 < M < 7$) and 17 stress axes obtained from structural analysis on Quaternary rocks. Notwithstanding the different scales and depths of the data considered in this work—near-surface for structural data, 0–6 km depth for breakouts, $\approx$3–20 km for earthquake focal mechanisms—the three distributions are surprisingly similar, all showing a predominant northeast-directed minimum horizontal stress in a broad region from the Tyrrhenian backarc through the Apenninic belt and up to the Apulian foreland. The belt, which corresponds to a region of high elevation, contemporary uplift and strong seismic release, with earthquakes as large as $M = 7$, is characterized by a normal-faulting stress regime. The breakout data demonstrate that the NE-oriented extension associated with the seismogenic normal faults of the southern Apennines is determined by a regional stress with $\sigma_3 = \mathrm{NE}$, in agreement with the seismological evidence that these faults are young (post-Middle Pleistocene). The breakout data show that even the foredeep and the most internal foreland region, where the (Apulian) foreland crops out, are dominated by northeast-oriented extension, even if we cannot establish the stress regime of this region due to the lack of seismicity. This suggests that a model in which the underthrusting Adriatic plate is in compression and in flexure, generating extension in the upper (Apenninic) plate, is not applicable, unless what we observe (NE-directed S_{hmin}) is limited to the upper part of the Adriatic plate, while its deeper portion might be in compression. Compared to the recent compressional tectonics that affected parts of the study region in the Upper Pliocene and Lower–Middle Pleistocene, it seems likely that an important change in the stress field occurred in this area during the Quaternary, most probably around 0.7 Ma. Considering the main tectonic processes acting in southern Italy—NNW convergence between Africa and Eurasia and subduction of Ionian and Adriatic lithosphere with associated slab pull and back-arc rifting—we speculate that the extension observed in southern peninsular Italy can be explained either by a slab window or by a buoyant subducted continental lithosphere in the upper mantle between the two active arcs, the northern Apennines and the Calabrian arc.

Key words: Italy, Quaternary, stress distribution, tectonics.

INTRODUCTION

The present-day geological setting of the Italian peninsula is very complex, as it is caused by the interaction of different geodynamic processes that have been acting closely in space and time. The result of these processes is a strongly variable present stress field, with regions in compression and regions in extension tightly spaced. Rebai, Philip & Taboada (1992) collected all of the active stress data available for the entire Mediterranean region, including microtectonic measurements, *in situ* stress data, earthquake focal mechanisms and volcanic alignments. The interpolated stress map calculated by Rebai *et al.* (1992) is widely used in numerical modelling of the Mediterranean (see e.g. Bassi & Sabadini 1994), but for the Italian region it suffers from a lack of data. In the study region (Fig. 1), only a few data relating to focal mechanisms

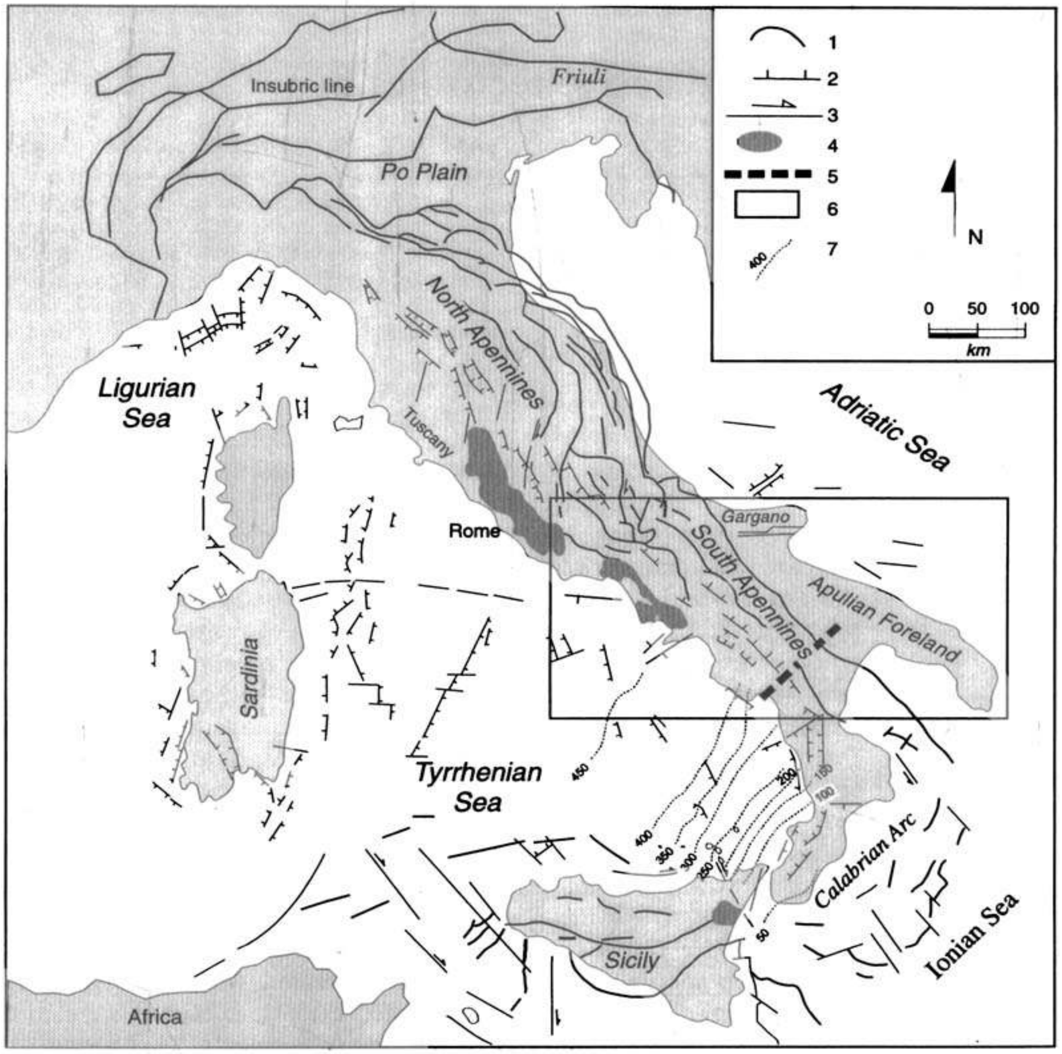

Figure 1. Structural map of the Italian Peninsula. (1) major thrust front; (2) major normal fault; (3) strike-slip and undetermined fault; (4) volcanic area; (5) cross-section location; (6) study area; (7) isobaths of the subducted lithosphere. Modified from Patacca & Scandone (1989) and Bigi *et al.* (1990).

are available along the Apenninic belt, and virtually no data exist for the Tyrrhenian coastal region and the Adriatic foredeep and foreland (i.e. within the Adria plate). Due to this lack of data, the definition of the regional stress field and the relationship with local sources of stress is a difficult task.

Italy is located between the African and European plates, which are presently converging in a N–S to NW–SE direction at a rate of less than 1 cm year^{-1} (Dewey *et al.* 1989; Argus *et al.* 1989; De Mets *et al.* 1990). Evidence of this convergence comes from satellite geodesy (Robbins *et al.* 1992; Ward 1994), *in situ* stress data, mostly collected in central Europe (Müller *et al.* 1992; Żoback 1992), and only in some regions from seismological data, i.e. focal mechanisms of earthquakes, as for instance in northeastern Africa (Jackson & McKenzie 1988). In Italy, only earthquakes that occur at the northern end of the Adriatic plate, such as the 1976 Friuli earthquakes, within the Adria plate itself (one $M_S=5.4$ in 1988) and around Sicily have focal mechanisms compatible with the main plate convergence (Anderson & Jackson 1987a; Pondrelli, Morelli & Boschi 1995). *In situ* stress data, mostly borehole breakouts in deep wells of the Iblean plateau (southeastern Sicily) also show NW–SE or NNW–SSE directions of S_{Hmax} (Cesaro 1993; Ragg, Grasso & Muller 1995; Montone *et al.* 1996). On the other hand, most of the strongest earthquakes (M up to 7) that occurred in peninsular Italy have normal-faulting solutions, indicating extension perpendicular to the Apenninic belt (Fig. 2), as shown by the fault plane solutions available for recent earthquakes (Gasparini, Iannaccone & Scarpa 1985; Anderson & Jackson 1987a; Pondrelli *et al.* 1995).

In the southern Apennines, a better knowledge of the present stress field is needed, both to provide constraints for geodynamic models of the region (see e.g. Bassi & Sabadini 1994; Giunchi *et al.* 1996) and for a better assessment of seismic hazard, that is where destructive earthquakes are likely to occur. In this paper, we focus on southern peninsular Italy, between latitudes N40° and N42°, from the Tyrrhenian to the Adriatic offshore. This is one step of an extensive study of the present-day stress field in the whole of the Italian Peninsula and Sicily using borehole breakouts and earthquake focal mechanisms that the Istituto Nazionale di Geofisica (ING) has promoted, in co-operation with Agip SpA (the National Oil Authority) and Enel SpA the National Electricity

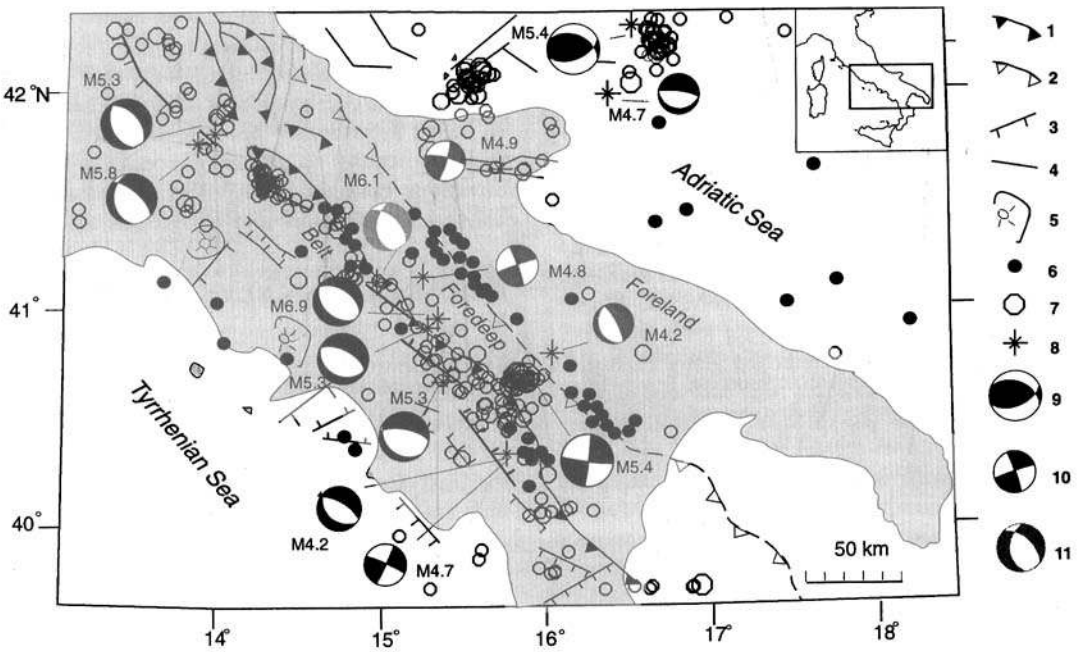

Figure 2. Distribution of the analysed deep wells compared with seismicity and focal mechanisms of the strongest earthquakes. (1) major overthrusts; (2) front of the allochthonous sheets; (3) normal faults; (4) strike-slip faults; (5) volcanoes; (6) well locations; (7) epicentres of $M>3$ earthquakes in the period 1986–1991; (8) epicentres of the strongest earthquakes ($M>4.0$); (9) CMT fault-plane solutions; (10) Gasparini *et al.* (1985); (11) Westaway (1987). Geological features from Patacca & Scandone (1989) and Valensise *et al.* (1993).

Authority). To date, this approach has been applied to several other regions in Italy, such as the geothermal areas in central Italy (Montone *et al.* 1995) and a small area in the northern Apennines (Montone *et al.* 1992).

The availability of hundreds of deep wells drilled by Agip in southern Italy in the last two decades offers us a unique opportunity to determine the stress directions in much greater detail than was previously possible. Amato, Montone & Cesaro (1995) reported results of breakout analysis on deep oil wells drilled in the southern Apennines. In this paper we describe and discuss these results in more detail, comparing them with other active strain and stress indicators, mainly earthquake focal mechanisms (Gasparini *et al.* 1985; Anderson & Jackson 1987a; Westaway 1987; Pondrelli *et al.* 1995) and mesostructural data from Pleistocene formations (Philip 1987; Rebai *et al.* 1992; Hippolyte, Angelier & Roure 1994). We also consider studies on crustal deformation inferred from large historical earthquakes (Westaway 1992; Valensise *et al.* 1993) and from satellite geodesy (Robbins *et al.* 1992; Ward 1994; Noomen *et al.* 1996) and the observed Quaternary uplift rates (Cosentino & Gliozzi 1988; Westaway 1993).

The main points we want to address are (1) if and how the present stress regime varies from the Tyrrhenian back-arc region, through the Apenninic belt to the Adriatic foredeep and foreland, (2) if the NE extension of the belt is continuous along the southern Apennines, as the few strongest earthquakes for which focal mechanisms are available suggest, and (3) if this NE extension is compensated by (aseismic) shortening in the Apenninic foredeep/foreland or along the Dinarides, as suggested by earthquake distributions (Anderson & Jackson 1987a).

GEOLOGICAL SETTING OF THE APENNINES

The present configuration of the Apennines consists of two major arcs, namely the northern Apennines and the southern Apennines (Fig. 1), separated by the N–S-trending Ortona–Roccamonfina fault zone (e.g. Locardi 1982; Bigi *et al.* 1990; Cocco *et al.* 1993), which according to some authors is related to a deep lithospheric discontinuity (Patacca & Scandone 1989; Amato *et al.* 1993). The presence of a continuous foredeep from the Po Plain to Sicily is connected with the flexure of a rigid foreland lithosphere. The formation of the foredeep is due to roll-back of the subducting Apulian continental lithosphere caused by slab pull, rather than to topographic and sediment loading (Royden & Karner 1984; Malinverno & Ryan 1986; Royden, Patacca & Scandone 1987; Patacca & Scandone 1989; Kruse & Royden 1994). Differential retreat of the flexing Adriatic plate beneath the northern Apennines (1.0–1.5 cm year^{-1}) and beneath the Calabrian arc (6 cm year^{-1}) caused the development of the two major arcs (northern and southern Apennines), according to Patacca & Scandone (1989) and Cinque *et al.* (1993).

From the Tortonian to the Quaternary, the co-existence of extension along the inner margin of the Apenninic belt and compression along the outer arcs of the peninsula is observed. Both compressional and extensional processes have been migrating from the Tyrrhenian region to the Adriatic foreland. The present deformational pattern is compressive along the buried outer thrusts of the Po Plain and offshore Central Adriatic Sea and in the external Calabrian arc (Finetti 1982; Patacca & Scandone 1989; Westaway 1992; Doglioni 1991; Montone *et al.* 1996). The regions where active compression is observed (northern Apennines and Calabrian arc) correspond to the areas where intermediate and deep seismicity occurs (Anderson & Jackson 1987b; Selvaggi & Amato 1992). At present, extension is localized in the Tyrrhenian margin of the northern Apennines and is observed both in the Quaternary volcanic belt of Central Italy from breakout and focal mechanism data (Montone *et al.* 1995) and along the Apenninic belt (Anderson & Jackson 1987a).

In the last 30 years, AGIP has drilled many deep wells and shot several reflection lines that have allowed a detailed interpretation of the deep structures in the southern Apennines (Mostardini & Merlini 1986). There is evidence for a complex thrust structure, with several nappes detached along subhorizontal fault planes, overthrust towards the east above the Adriatic foreland. Fig. 3 shows the three main tectonostratigraphic units that form the upper-crustal stack of the southern Apennines. From east to west we recognize (1) the 'external' (eastern) Adriatic foreland, comprised of a 7–8 km thick Meso–Cenozoic carbonate platform sequence, (2) the allochthonous basinal Lagonegro and Molise units, consisting of a sequence up to 4–5 km thick of marls, siliceous carbonates and terrigenous sediments, and (3) the 'internal' (western) Apenninic carbonate platform (Scandone 1967; D'Argenio, Pescatore & Scandone 1973). Both the foredeep and some intramontane basins are filled with terrigenous sediments deposited during the Pliocene and the Quaternary (Mostardini & Merlini 1986). In the geological sections presented by these authors, the Plio–Pleistocene sediments are cut by shallow-dipping thrusts, but the age of the most recent compressional features is not clearly established.

The Triassic–Early Miocene Apulian platform, cropping out in Apulia and in the northern Adriatic Sea, dips westwards beneath the allochthonous cover (Lagonegro and Molise units) and is found at depths greater than 3–4 km beneath the Apenninic belt (Mostardini & Merlini 1986). According to these authors, the Apulian platform was only slightly involved in the compressional tectonics that affected the Apennines after Tortonian times (7 Ma), whereas the basinal units overlying the Apulian platform were affected by thin-skinned tectonics with a high degree of shortening (see Fig. 3). In contrast to the suggestions of Mostardini & Merlini (1986), Casero *et al.* (1988) suggested that the Apulian platform beneath the Apenninic thrusts is characterized by a high degree of tectonization and shortening, which also involved the underlying basement, at 10–15 km depth.

Some of the deep wells that were drilled within the Apenninic belt are of particular interest because they penetrate both the allochthonous basinal units and the underlying Apulian platform at a depth of about 4000 m. Therefore, they allow us to define its geometry beneath the Apennines, and also offer the opportunity to determine possible variations of stress directions between the Apulian platform and the overlying allochthonous nappes and terrigenous units (Fig. 3).

BREAKOUT ANALYSIS: METHOD AND RESULTS

The generation of breakouts is interpreted as being the result of localized shear failure in response to a concentration of compressive stress within an anisotropic stress field (Bell & Gough 1983). The breakouts are aligned in the direction of the least horizontal stress (S_{hmin}). Cox (1970) was the first to note intervals along boreholes with elliptical cross-sections, and associated this with the active stress field. This approach was then applied by Babcok (1978) and afterwards by a number of researchers in many regions of the world to investigate the active stress field (see Zoback 1992 and references therein).

Borehole breakouts now represent 28 per cent of the WSM database (Zoback 1992). In Europe, this percentage is significantly lower (14 per cent), and in Italy was only 1 per cent in 1992. More recently, stress directions inferred from borehole breakouts were determined by Montone *et al.* (1992, 1995) and Amato *et al.* (1995) for peninsular Italy and Cesaro (1993) and Ragg *et al.* (1995) for Sicily.

To identify breakouts we use readings from a four-arm caliper, which is part of the dipmeter logging tool. The four-arm caliper has four extendible pads, one of which is magnetically oriented and records the long and short axes of a borehole and their azimuths. In the analysis of both paper and digital

Table 1. Quality ranking system for breakout orientations (Zoback 1992).

Length	standard deviation			
	<12°	<20°	<25°	>25°
>300 m	A	B	C	D
100–300 m	B	C	D	E
30–100 m	C	D	E	E
0–30 m	D	E	E	E

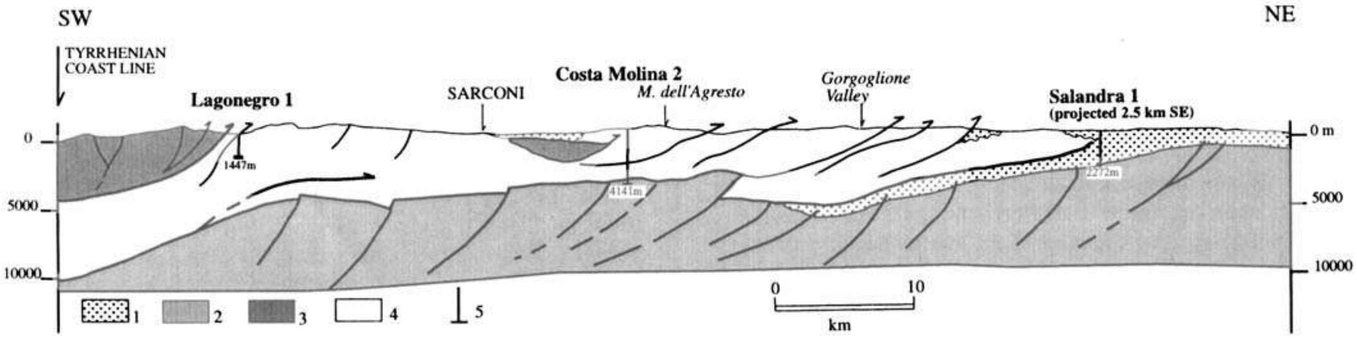

Figure 3. Geological cross-section of the southern Apennines. (1) Marine sedimentary sequence, Middle–Upper Pliocene–Quaternary; (2) Apulian platform (prevalent calcareous–dolomitic sequence), Trias–Cenozoic; (3) Apenninic platform (prevalent carbonates), Trias–Cenozoic; (4) 'Lagonegro–Molisan' basinal unit (calcareous–siliceous–marly sequence), Trias–Cenozoic. The names in boldface show the locations of the wells (5). Simplified from Mostardini & Merlini (1986).

logs, we followed the criteria suggested by Plumb & Hickman (1985) for breakout identification [see Amato *et al.* (1995) for a description of the technique and of quality assessment (Table 1)].

Amato *et al.* (1995) reported results from several wells located in a 200 km (N–S) by 400 km (E–W) area from the Tyrrhenian sea to the Adriatic foreland (Fig. 2). Here, we describe these breakout results and compare them with other stress indicators (see next sections).

Table 2 shows the data listing for each well (only qualities A to D, no E or 'circular' wells, are reported), including bottom depth, total breakout length, breakout interval, breakout azimuth, standard deviation and assigned quality. This table is in substance very similar to Table 1 of Amato *et al.* (1995), but with some slight differences due to recomputation of some log intervals for a few wells. We report the whole breakout data set in Table 2.

Breakout results for the Tyrrhenian coastal margin

In this area (Fig. 4) we have analysed six wells that drilled a sedimentary sequence consisting of clays, sands and gravels (mostly Quaternary), Eocene allochthonous units, and only in one case Meso–Cenozoic limestones of the underlying Apenninic platform. (Table 2, wells T1 to T5, one well was discarded.)

For wells T1, T2 and T5 we found NE–SW to ENE–WSW S_{hmin} directions, perpendicular to the major normal-fault systems of the area (Bigi *et al.* 1990). The two different directions of S_{hmin} detected in the same region (wells T3 and T4) are probably due to the presence of local structures, mainly NE-trending normal faults that may have acted as transfer faults of the main fault system. Locally, NE- or E-trending compressional features in this area are also documented by seismic-reflection studies (Sacchi, Infuso & Marsella 1994).

Table 2. Main characteristics of the wells (qualities from A to D) in which we performed the breakout analysis. Wells are listed with codes: T—wells in the Tyrrhenian area; B—in the belt; FD—in the foredeep; FL—in the foreland; n = northern sector; s = southern sector. Heavy type codes indicate paper log data, the others codes are for digital logs.

WELL	bottom (m)	breakout length (m)	breakout interval (m)	bo azimuth ± sd (°)	Qual.
T1	2072	130	1205–1583	N076 ± 25	C
T2	2040	145	1200–1830	N040 ± 30	D
T3	3000	184	1718–2910	N123 ± 28	D
T4	3482	355	1027–3453	N169 ± 16	B
T5	2911	45	509–1636	N056 ± 11	C
Bn1	4212	585	600–850 3150–3991	N038 ± 11	A
Bn2	3122	106	2000–2926	N047 ± 18	C
Bn3	3890	185	3250–3835	N035 ± 14	B
Bn4	3720	122	3083–3617	N105 ± 15	D
Bn5	4510	622	1250–4480	N045 ± 17	B
Bn6	3850	245	2775–3275	N169 ± 08	B
Bn7	2673	64	1506–2390	N030 ± 21	C
Bn8	2995	570	1330–2452	N069 ± 08	A
Bs1	4405	253	3753–4367	N041 ± 12	B
Bs2	4910	154	4224–4638	N042 ± 24	C
Bs3	4722	17	3203–4603	N029 ± 25	D
Bs4	4390	149	2307–3723	N013 ± 33	D
Bs5	4090	12	1700–2971	N023 ± 20	D
Bs6	3862	118	3153–3776	N052 ± 10	B
Bs7	4166	30	3670–3927	N043 ± 22	C
FDn1	1852	138	158–691	N013 ± 23	D
FDn2	1682	317	150–1625	N023 ± 10	B
FDn3	2523	87	2072–2270	N008 ± 16	C
FDn4	2511	428	313–2412	N054 ± 27	C
FDn5	2100	20	1217–1925	N109 ± 19	D
FDn6	2200	128	1396–1616	N076 ± 04	C
FDn7	3318	57	1521–3315	N036 ± 27	C
FDn8	4903	540	1181–4293	N112 ± 26	D
FDn9	2502	457	1000–2500	N068 ± 12	B
FDn10	4493	76	2431–4482	N038 ± 23	C
FDn11	2995	471	982–2496	N072 ± 17	B
FDn12	1620	144	472–999	N013 ± 21	C
FDs1	2146	137	410–1313	N001 ± 17	D
FDs2	1952	77	901–1886	N035 ± 31	D
FDs3	2540	135	1550–2440	N001 ± 12	C
FDs4	2505	44	1342–2469	N158 ± 21	D
FDs5	1173	15	400–1044	N056 ± 25	D
FDs6	3154	179	2750–3145	N026 ± 10	B
FDs7	1142	274	197–885	N026 ± 14	B
FDs8	2525	26	1729–2086	N068 ± 16	C
FL1	7070	583	972–4928	N064 ± 23	C

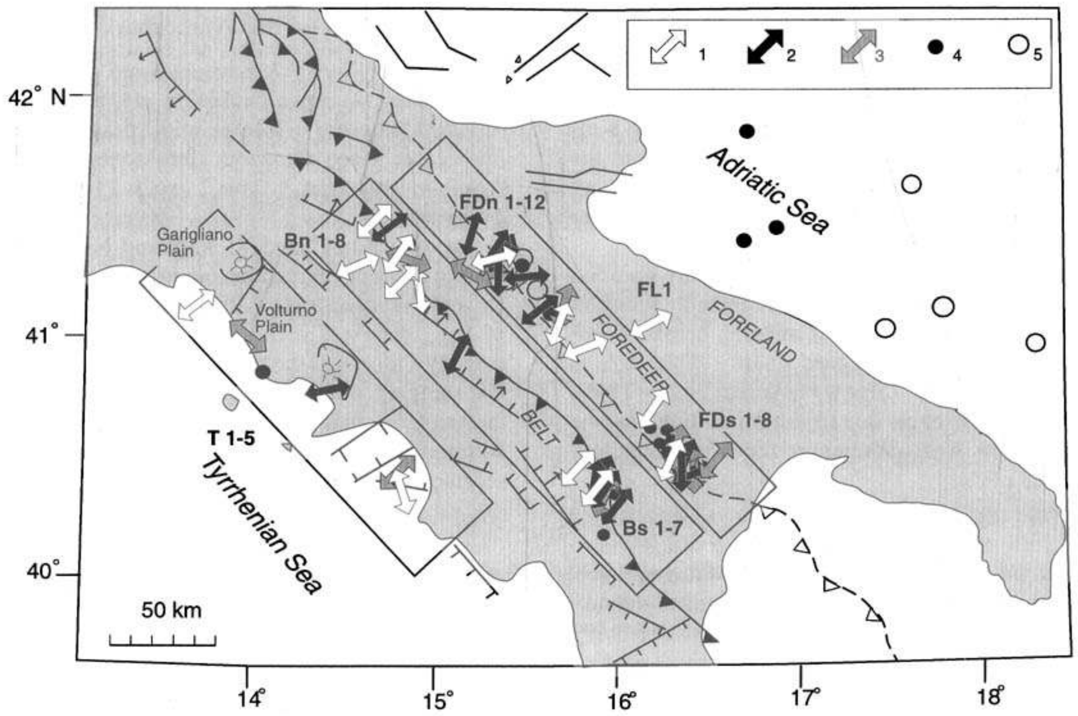

Figure 4. S_{hmin} directions from breakout analysis according to data quality. (1) quality A and B; (2) quality C; (3) quality D; (4) discarded wells; (5) undeformed wells. For tectonic symbols see Fig. 2.

Based on the entire data set for the Tyrrhenian margin, including the results obtained by Montone *et al.* (1995) in the back-arc region of the northern Apennines, and looking at the recent tectonic evolution of the region, it is reasonable to conclude that at a regional scale (i.e. $\approx$100–500 km) the stress field along the margin is still dominated by NE extension, with evidence of local-scale ($\approx$10–50 km) stress rotations.

Breakout results for the Apenninic belt

We analysed 19 wells in the Apenninic belt, 15 of which gave valuable results. These wells are located along the main front of the belt (Fig. 2) and are drilled through Cretaceous–Eocene allochthonous units, sometimes reaching the underlying Apulian platform below 3–4 km depth.

Breakouts, in most of these wells, provide a preferred NE–SW direction of S_{hmin} (Fig. 4), with very consistent directions between N40°E and N50°E for the Apulian platform (see Amato *et al.* 1995) and more scatter in the upper units. This result is in close agreement with that suggested from the focal mechanisms of earthquakes that have occurred in this region (Fig. 2), which reveal a normal-faulting stress regime along the entire Apenninic belt. Therefore, in this region we also associate the NE direction of S_{hmin} with σ_3. Also, considering the predominance of normal-faulting earthquakes in this region, we associate σ_{v} with σ_1. Since the width of the seismic belt in the southern Apennines is only about 30–40 km, with very few earthquakes occurring in the adjacent foredeep (Fig. 2), we cannot establish whether the normal-fault regime is limited to the belt or whether it extends towards the foredeep and the foreland (see below).

Breakout results for the Apenninic foredeep

20 wells located along the foredeep (Figs 2 and 4) gave valuable results from breakout analysis. Fig. 2 shows that many of the wells are located in the foredeep region, where seismicity is low or absent. Breakouts here are therefore particularly important in constraining the active stress field between the extending Apenninic belt and the stable Adriatic plate. Wells in this region are less deep than those in the belt on average, ranging mostly between 2 and 3 km (only two wells exceed 4 km). They penetrated the terrigenous sediments of the foredeep, reaching the autochthonous formations of the Apulian platform only in a very few cases. Although the observed directions show a larger scatter than the wells in the belt, a NE-trending S_{hmin} also dominates in this area: 16 out of 20 wells have S_{hmin} directions between N–S and N76°E; the other four are D quality. From the few fault-plane solutions available in this region, we cannot assess if the stress field in the foredeep is normal or strike slip.

Breakout results for the Apulian and Adriatic foreland

The foreland of the southern Apennines corresponds geographically with the emerged Apulian region and the southern Adriatic sea, both made up of Meso–Cenozoic undeformed limestone and dolostone rocks (Fig. 1). According to Doglioni, Mongelli & Pieri (1994), the Apulian block emerged because of the bulge due to subduction of a thicker lithosphere in this region compared with the northern Adriatic. In this region we have analysed eight wells, seven of which are located in the Adriatic sea, up to ~70 km from the Apulian coast. Three of these offshore wells were discarded, and in the other four wells no breakouts were detected. As proposed by Amato *et al.* (1995), plausible explanations are either a horizontally isotropic stress, or higher rock strength, which impeded the microcrack formation necessary to determine the genesis of a breakout.

The only well (FL1) located onshore in the Apulian foreland gave a very interesting result (Fig. 4). It is a 7 km deep well that penetrated the entire limestone platform sequence (from Triassic to Early Miocene). The breakouts in this well revealed an orientation of S_{hmin} of N64°E, similar to those found in the belt and foredeep region (N40°–50°E). This suggests that the stress field that dominates in the whole southern Apenninic sector (NE-directed extension) extends within the foreland region at least 30–40 km from the outer thrust front (Figs 1 and 2), although rotated by about 20°.

Towards the east, this extensional NE-oriented stress field seems to die off into an almost horizontal isotropic stress. The N64°E direction of S_{hmin} computed for well FL1 (Table 2, Fig. 4) is observed throughout the entire drilled interval ($\approx$900–$\approx$6100 m) within the Apulian platform (the foreland), which to the west bends and underthrusts the nappes of the Apenninic belt.

The well closest to FL1 towards the foredeep (west) is FDn1, for which an almost identical direction of S_{hmin} was observed (N66°E, quality B). Unfortunately, we cannot assess how far to the east this NE orientation of S_{hmin} extends, as there is a distance of about 100 km between well FL1 and the undeformed wells of the Adriatic sea (Fig. 4).

YOUNG GEOLOGICAL DATA

Field analysis of tectonic structures is a basic tool in the study of the stress field. At outcrop scale, microstructural observations such as striated fault planes, striated pebbles, tension gashes and stylolites can be used with numerical methods to infer the orientation and the relative magnitudes of the stress tensor (see e.g. Carey & Brunjer 1974; Armijo & Cisternas 1978; Angelier 1979; Gephart & Forsyth 1984; Michael 1984). Since these measurements are relative to rock formations of different ages, it is often difficult to assess their relationship with the active stress field, particularly in regions where important variations have occurred in Quaternary times, as may be the case of the southern Apennines (see next section). Of course, the more recently such a stress change takes place, the more difficult will be to find its signature in tectonic structures.

In this section, we review the mesostructural data available in the young geological units of the southern Apennines. As will be shown, these data are limited to a few measurements and are generally spread in broad regions, at least as far as the most recent (< 1 Ma) deformational features are concerned (Hippolyte *et al.* 1994). The mesostructural analysis provides a numerical estimate of the stress tensor (the directions of the three σ and R), but the computed stress directions can be affected by local sources and therefore they may not represent the regional stress field, as discussed in Rebai *et al.* (1992) and Zoback (1992).

The most recent compilation of stress data for the entire Mediterranean region, including mesostructural data in southern Italy, is by Rebai *et al.* (1992). Most of the geological data reported in this paper for the study region come from Philip (1983). We considered all the data compiled by Rebai *et al.* (1992), even where we could not definitely assess the precise ages of all reported deformational features, since the directions reported in Table 1 of Rebai *et al.*'s paper are generically classified as being of Quaternary age. In Table 3 and Fig. 5 we report 10 directions of σ_1 and σ_3 taken from Rebai *et al.* (1992), seven of which are related to normal-faulting stress regimes and three of which are compressional (two in Apulia with N–S compression, and one in the foredeep). We also report (Table 3, Fig. 5) seven directions of σ_3 determined by Hippolyte *et al.* (1994), all relative to a normal-faulting regime associated with NE extension. Hippolyte *et al.* (1994) proposed that the stress field in the southern Apennines changed after the early Middle Pleistocene, based on the age of the geological formations in which the different fault populations were analysed. After $\approx$0.7 Ma, the stress field has been dominated by diffuse NE extension. Similarly to the method used for borehole breakouts and focal mechanisms, a quality factor has been assigned to each stress direction considered in this study. To do this, we referred to the ranking system of the World Stress Map (WSM) (Zoback 1992), taking into account the original quality assigned by the authors. For microtectonic measurements, we used qualities provided by Rebai *et al.* (1992), which were assigned according to the number and distribution of fault planes, the angular difference between calculated and measured striations, and the mechanical reliability of the solution in terms of friction laws.

Also shown in Fig. 5 are the Middle–Late Pleistocene (post-700 ka) uplift rates observed in Southern Italy (Cosentino & Gliozzi 1988; Westaway 1993). A general uplift rate of up to 1 mm year^{-1} is observed along the southern Apenninic belt, whereas a lower rate of uplift is detected in the Apenninic foredeep (0.5–0.7 mm year^{-1}) and in the Apulian foreland (0.2–0.3 mm year^{-1}). Large uplift rates ($\approx$ 1 mm year^{-1}) characterize the entire Calabrian arc (Cosentino & Gliozzi 1988; Westaway 1993), while in southern and western Sicily rates of less than 0.2 mm year^{-1} are observed. Negligible uplift was measured in a few sites along the Tyrrhenian coast of Campania.

The decreasing pattern of uplift rate observed from the southern Apenninic belt ($\approx$1 mm year^{-1}) to the foredeep ($\approx$0.5 mm year^{-1}) up to the Apulian foreland ($\approx$ 0.2 mm year^{-1}) seems to be somehow connected with the seismic release, which is high in the belt (with vertical σ_1), moderate in the foredeep, with normal and strike-slip earthquakes, and almost zero in the Apulian foreland (Figs 2 and 5).

It is also interesting to note that the flexing of the Adriatic plate beneath the Apennines, described for the northern Apennines by Kruse & Royden (1994) for the Pliocene, seems to have stopped during the Quaternary, suggesting a direct relation between the mantle processes acting on the subducted lithosphere and the surface tectonic evolution. This can also be hypothesized from the comparison between crustal stress and deep structures inferred from tomography and seismicity distribution (Montone *et al.* 1996).

EARTHQUAKE FOCAL MECHANISMS

Fig. 2 shows the epicentres of recent seismic events and selected fault-plane solutions available for the study region. The seismicity is concentrated in a narrow (30–40 km) area along the axis of the belt, whereas very few earthquakes occur along the Adriatic foredeep and in the Apulian/Adriatic foreland.

Table 3. Main characteristics of the Quaternary mesostructural data of the southern Apennines. Ref. = 1: Hippolyte *et al.* 1994; 2: Rebai *et al.* 1992. Strike and dip of σ_1, σ_3 and strike of S_{Hmax}, S_{hmin} are listed from Ref. 1 and Ref. 2, respectively. SR = stress regime. Region = see codes of Table 2. Qual. = quality factor according to Zoback (1992).

No.	Ref.	Lat–Lon	$\sigma 1/S_{\mathrm{Hmax}}$	$\sigma 3/S_{\mathrm{hmin}}$	SR	Region	Age of tectonics	Qual.
1	1	41.37–13.89	147–66	239–01	NF	T — Roccamonfina	M–L Pleist.	A
2	1	41.16–14.50	249–67	010–12	NF	B — Benevento	M–L Pleist.	A
3	1	40.95–15.21	216–74	070–13	NF	B — Irpinia	M–L Pleist.	A
4	1	40.70–15.34	284–69	014–01	NF	B — Irpinia	M–L Pleist.	A
5	1	40.56–15.47	120–70	216–02	NF	B — Irpinia	M–L Pleist.	A
6	1	40.29–15.71	298–85	066–03	NF	B — Vallo di Diano	M–L Pleist.	A
7	1	40.56–16.32	086–78	214–08	NF	FD	M–L Pleist.	A
8	2	41.10–15.02	175	085	NF	B — Benevento	Quaternary	B
9	2	40.75–14.45	132	042	NF	T — Vesuvio	Quaternary	B
10	2	40.90–15.54	067	157	NF	Vulture	Quaternary	A
11	2	40.48–15.30	125	035	NF	B — Irpinia	Quaternary	B
12	2	40.60–14.95	170	080	NF	T — Sele Plain)	Quaternary	A
13	2	40.51–14.85	122	032	NF	T — Sele Plain	Quaternary	A
14	2	40.03–18.18	010	100	TF	FL — Salento	Quaternary	B
15	2	40.47–16.56	035	125	TF	FD	Quaternary	B
16	2	40.30–15.90	034	124	NF	B — Val d'Agri	Quaternary	A
17	2	41.61–15.52	018	108	TF	FL — Gargano	Quaternary	A

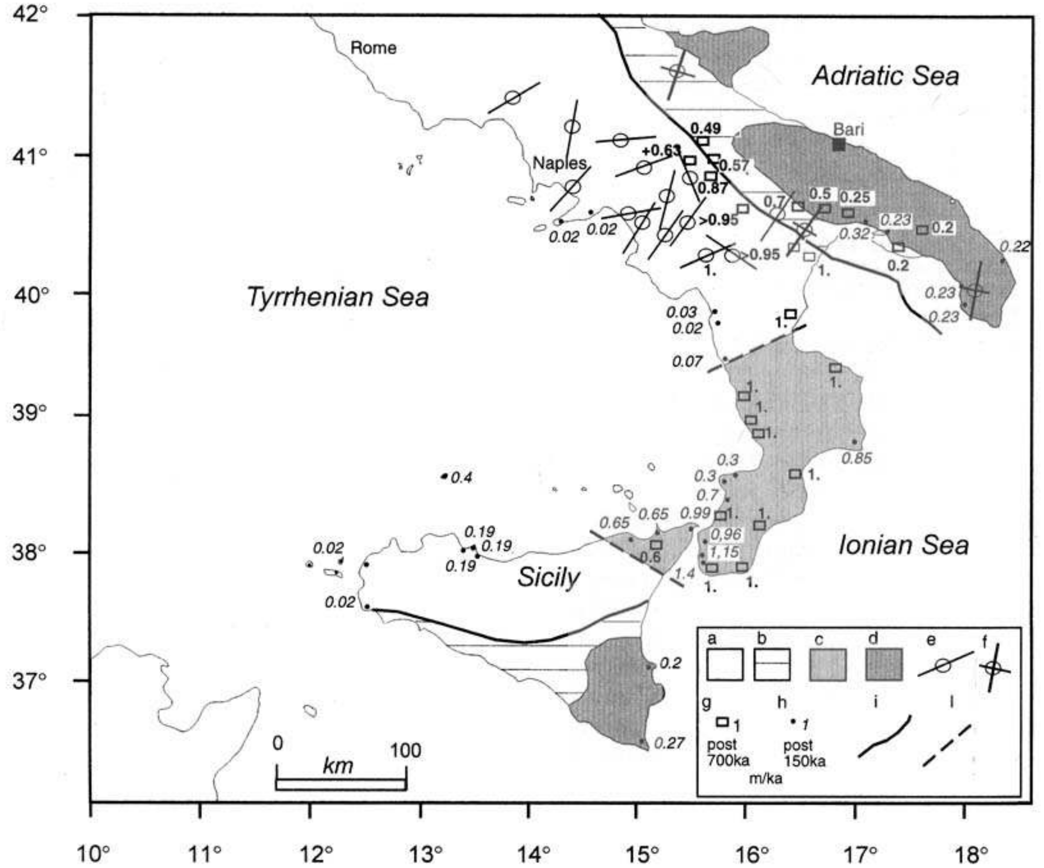

Figure 5. Mesostructural and morphological data: (a) belt unit; (b) foredeep unit; (c) Calabrian unit; (d) foreland unit; (e) and (f) σ_3 or S_{hmin} direction and σ_1 or S_{Hmax} direction from mesostructural data (Hippolyte *et al.* 1994; Rebai *et al.* 1992; see also Table 4); (g) uplift value in m ka^{-1} (Westaway 1993); (h) uplift value in m ka^{-1} (Cosentino & Gliozzi 1988); (i) external front of the allochthonous unit; (l) Calabro–Peloritan boundary.

For Italy, most of the data included in the WSM compilation (around 90 per cent) are focal mechanisms of earthquakes (Zoback 1992). These are either CMT solutions (Fig. 2) or polarity solutions computed by Anderson & Jackson (1987a) and Westaway (1987) with teleseismic data, and by Gasparini *et al.* (1985) with regional bulletin data for smaller earthquakes. This implies that no real stress data are available, since earthquake focal mechanisms are indicators of strain. If, for instance, the seismic strain is mostly accommodated on pre-existing faults, possibly unfavourably oriented to the present stress field, the inference of active stress directions from focal mechanisms would be misleading. As already pointed out by

Amato *et al.* (1995) for the southern Apennines and Montone *et al.* (1995) for the Tyrrhenian margin of the northern Apennines, there is in general a good correspondence between average extensional axes of earthquakes and the S_{hmin} direction inferred from breakouts.

The CMT solutions available for the study region (Table 4) include only seven earthquakes that occurred between 1980 and 1994, among which six were located in the Apenninic belt and only one occurred within the Adriatic plate, in 1988 ($M_S = 5.4$) with a reverse-faulting mechanism, showing N–S compression. The six Apenninic earthquakes include two similar events that occurred in 1984 between Latium and Abruzzi ($M_S = 5.3$ and 5.8), three shocks that occurred in 1980 and 1981 in the Irpinia region ($M_S = 5.2$–6.9), all with pure normal-faulting mechanisms showing NE extension, and one earthquake that occurred in 1990 in the region of Potenza, with a moment magnitude $M_W = 5.8$ and a strike-slip solution associated with NE extension (Azzara *et al.* 1993; Ekstrom 1994). This earthquake and related aftershocks occurred on an E–W-trending fault at a depth of between 15 and 25 km, and was followed, one year later, by another similar earthquake of $M_W = 5.2$, in the same location and with the same focal mechanism (Ekstrom 1994). These two events are located in a more external (eastern) region and at a greater depth than the Irpinia earthquakes (see Fig. 2), suggesting that the different focal mechanisms between Irpinia (= belt) and Potenza (= belt to foredeep) reflect the transition between a normal-faulting region and a strike-slip region. Unfortunately, the 1990 Potenza earthquake is the only seismic event of the 'belt to foredeep' region for which a reliable focal depth is available. Based on a few more, poorly constrained hypocentral depth locations reported by Gasparini *et al.* (1985), Hippolyte, Angelier & Barrier (1995) observed that all the earthquakes in this area (the northeasternmost part of the belt) occurred in the underlying (external, or Adriatic) plate, whereas the seismicity of the belt occurs entirely in the upper (internal, or Apenninic) plate. If this is true, we can speculate that the whole crustal stack made up by the Apenninic thrust sheets (including the internal Apulian platform and the more internal basinal and platform units of the Tyrrhenian side) is undergoing extension (with $\sigma_1 = \sigma_V$), while the flexed and perhaps uplifting underlying plate is affected by along-axis compression ($\sigma_1 = S_{\mathrm{Hmax}} =$ NW–SE) accompanied by NE–SW extension (σ_3). However, we do not consider the hypocentral depths reported in the bulletins to be reliable, because they were determined with a sparse regional seismic network (as was the Italian network in the 1970s), and therefore the considerations reported above are still speculative.

The polarity solutions reported in Table 4 (Ref. 2) are selected from Gasparini *et al.* (1985). The magnitudes of these earthquakes, which occurred between 1967 and 1980, range from 4.2 to 4.9 (M_b from ISC bulletins). Also added in Table 4 are two focal mechanisms of $M \approx 6$ earthquakes that occurred in the Irpinia region in 1962 (Westaway 1987). The solutions calculated by Westaway (1987) have tensional (T) axes oriented ENE, with oblique P axes. We assigned qualities to these solutions (Table 4) based on the number and distribution of polarities and reported discrepancies. The CMT solutions also have a quality factor assigned, following the criteria suggested by Zoback (1992). Fig. 2 shows all the solutions collected. It is evident that most of the earthquakes have normal-faulting mechanisms with NE extension, some have strike-slip solutions with a similar direction of extension, and only a few have different mechanisms.

Since, as described above, only a few reliable fault-plane solutions are available for the study region, other important information to infer the present deformational pattern and hence the active stress field can be obtained by looking at the locations of large ($M \approx 7$) historical earthquakes and comparing them with the geological structures generated by these events, observed either directly in the field or from geomorphology (Westaway 1993; Valensise *et al.* 1993). The former structures are relative only to faults that ruptured the surface, as for instance the 1980 Irpinia earthquake fault (Westaway & Jackson 1987; Pantosti & Valensise 1990) and are unfortunately limited to very few palaeoseismological studies. The latter are more uncertain, because the association between large historical earthquake ruptures and surface geological features is much more difficult to assess. However, there is evidence that most of the large earthquakes that occurred in the last few centuries in the central–southern Apennines had normal-faulting mechanisms, and that the associated faults are 'young' (Pantosti,

Table 4. Main characteristics of the major earthquakes of the southern Apennines. Ref. = 1: Westaway (1987); 2: Gasparini *et al.* (1985); 3: CMT solutions. Mag. = from macroseismic intensity (events 1, 2), M_b (events 3–10), M_S (events 11–17). SR = stress regime. Region = see codes of Table 2. Qual. = quality factor according to Zoback (1992).

No.	Date	Ref.	Mag.	Lat–Lon	T-axis str. pl.	P-axis str. pl.	SR	Region	Qual.
1	620821	1	5.7	41.12–15.02	073–07	170–46	NF	B (Irpinia)	D
2	620821	1	6.1	41.13–14.95	063–14	174–56	NF	B (Irpinia)	B
3	671209	2	4.7	42.00–16.50	007–29	188–62	NF	FL (Gargano)	C
4	710506	2	4.8	41.20–15.24	207–07	297–02	SS	B (Irpinia)	C
5	711129	2	4.7	40.34–15.77	248–08	158–03	SS	B (Val d'Agri)	C
6	730808	2	4.6	40.72–15.41	154–22	256–28	SS	B (Irpinia)	D
7	731030	2	4.4	41.70–13.87	244–22	134–39	U	B (Val Comino)	D
8	750619	2	4.9	41.65–15.73	239–21	147–05	SS	FL (Gargano)	C
9	780924	2	4.2	40.80–16.11	066–26	238–63	NF	FD (Bradano)	C
10	800514	2	4.2	40.36–15.77	034–26	197–74	NF	B (M. Alpi)	C
11	801123	3	6.9	40.91–15.37	039–04	163–82	NF	B (Irpinia)	B
12	801125	3	5.3	40.65–15.40	020–21	170–66	NF	B (Irpinia)	C
13	810116	3	5.3	40.95–15.37	027–15	212–75	NF	B (Irpinia)	C
14	840507	3	5.8	41.77–13.89	057–19	189–63	NF	B (Val Comino)	B
15	840511	3	5.3	41.83–13.95	056–03	164–80	NF	B (Val Comino)	C
16	880426	3	5.4	42.37–16.57	279–68	177–05	TF	FL (Adriatic)	B
17	900505	3	5.4	40.75–15.85	046–21	138–03	SS	B–FD (Potenza)	B

Schwartz & Valensise 1993; Westaway 1993), that is they developed after 0.7 Ma.

This approach provides indications on the regional seismic deformation (a $M \approx 7$ earthquake fault affects an area of several hundreds of square kilometres), but the relationship of this deformation with the regional stress is not always straightforward, depending on the rheological properties of the faults. Along large, crustal-scale strike-slip faults [such as the San Andreas fault in California and the Great Sumatran fault in Sumatra, see Zoback *et al.* (1987) and Mount & Suppe (1992)] it has been shown that the angle between the maximum stress and the strike of the fault is high (80–90°), indicating low shear stresses on the faults, which must therefore be inherently weak surfaces (Mount & Suppe 1992). In the southern Apenninic belt, however, the very young age of the extensional tectonics, and the observation of newly generated faults during strong earthquakes (Westaway & Jackson 1987; Pantosti & Valensise 1990) suggest that the direction of extension (NE–SW) does correspond with the regional minimum compressive stress σ_3. As described above, the breakout data have demonstrated this correspondence for southern peninsular Italy.

DISCUSSION

The actual state of the stress in the lithosphere is determined by the interaction of several forces, primarily surface and subsurface loading, as for instance lateral density variations in the upper mantle and associated topographic loading. In regions of subducting plate boundaries, Whittaker, Bott & Waghorn (1992) have shown that compression in the trench region is caused by the dense sinking slab and the related surface downflexure, whereas tension is generated in the presence of a weak subduction fault and crustal thickening, and in the back-arc region by low-density upwelled asthenosphere. The Late Neogene to Quaternary evolution of the Italian Peninsula has been mainly controlled by the Africa–Adria–Europe plate interaction and by westward subduction of Adriatic and Ionian lithosphere and the related opening of back-arc basins. We therefore believe that the knowledge of the present-day stress field in the crust is crucial to the understanding of the active processes, and offers a key to unravel the complex geological evolution of southern peninsular Italy.

The number and complexity of the processes acting simultaneously in southern Italy can explain why very few attempts of modelling such a complex region have been made to date. These are limited to some two-dimensional finite-element models, either horizontal (e.g. Bassi & Sabadini 1994) or vertical (Giunchi *et al.* 1996). Alternatively, some qualitative mechanisms have been proposed in order to explain one particular observation, not considering all the available data, their geographical location and their validity. For instance, Hippolyte *et al.* (1995) used the results obtained by Kruse & Royden (1994) for the northern Apennines to explain the extension in the southern Apennines, even though the two regions underwent a very different geodynamic evolution (Patacca & Scandone 1989) and are presently characterized by different tectonic settings and stress fields (Montone *et al.* 1996). Westaway (1993) attributed the Quaternary uplift of southern Italy to slab detachment and the consequent isostatic response, without considering the downward suction that the detached sinking slab would exert on the overlying lithosphere, as demonstrated by numerical simulation (Giunchi *et al.* 1996). Therefore, after summarizing the main results outlined in this paper, we describe the main sources of stress in southern Italy and for each of them we try to assess what the uncertainties and limitations are.

The main result of this study is the recognition of a widespread NE-oriented extension in a broad region of southern peninsular Italy. This region includes different geological provinces that have been affected by the Apenninic orogenic processes at different times, starting from the Miocene in the west (the Tyrrhenian margin) to the Pliocene (–Lower Pleistocene?) in the belt and up to Lower (–Middle?) Pleistocene in the foredeep (Bigi *et al.* 1990). The compressional phases that led to the emplacement of the allochthonous units and to the development of thrust and reverse faults were followed by NE–SW extension, approximately perpendicular to the trend of the mountains. This extension is evident in the back-arc (western) region, where it has been active for a longer time, as shown by well-developed 'horst and graben' structures oriented NW–SE or NNW–SSE (Figs 1 and 2). In this region the extension was also accommodated by transverse (NE-oriented) basins, such as the Volturno and Garigliano valleys (Fig. 4), interpreted either as 'transfer' basins that accommodate areas with variable rates of NE extension, or as extensional structures due to a NW–SE-directed σ_3 that followed a previous parallel compression (Hippolyte *et al.* 1995).

Our results in the Tyrrhenian region show a predominant NE direction of S_{hmin}, with some deviations probably due to local sources of stress. The NE direction of S_{hmin} is interpreted as the regional minimum horizontal stress, most likely corresponding to σ_3, as there is no evidence of young thrust tectonics in this region. The conclusion that the present-day stress field along the entire Tyrrhenian region is characterized by NE extension is also based on stress data recently published for the adjacent region of Latium and Tuscany (Montone *et al.* 1995). In this region the coexistence of normal and strike-slip focal mechanisms with a common σ_3 is indicative of a stress field with $\sigma_1 = \sigma_V \sim \sigma_2 = S_{\mathrm{Hmax}}$ (NW–SE) $>> \sigma_3 = S_{\mathrm{hmin}}$ (NE–SW).

At the regional scale (that is from Tuscany to Campania along the entire Tyrrhenian margin of the Apennines, length $\approx$ 500 km), a recent extensional pulse is testified by the abrupt onset of volcanic activity around 0.7–0.5 Ma (Barberi *et al.* 1994). Many volcanoes in this region developed in this time period and they are aligned parallel to the belt (NW–SE), thus perpendicular to the regional direction of extension (NE–SW).

The breakout data presented in this paper indicate that the NE-oriented direction for the minimum compressive stress is spread in a broad region, including the belt, the foredeep and, to a certain extent, the Apulian foreland. It is important to note that the minimum compression perpendicular to the trend of the Apenninic mountain range is observed both in the upper allochthonous cover and in the underlying Apulian platform at 4–5 km depth (or more) beneath the thrust sheets (Fig. 3). This implies that the entire brittle crust is undergoing NE extension, as also witnessed by focal mechanisms of earthquakes in the 0–15 km depth range. According to Hippolyte *et al.* (1995), this NE extension is characteristic of the 'upper plate', that is the upper 10–15 km of the overthrust crustal stack that overlies the Apulian basement, from which it is separated by a décollement.

Coeval with the extensional pulse described for the Tyrrhenian region (Barberi *et al.* 1994), a major change in the stress field has been proposed to have occurred in the belt around 0.7 Ma, based on the observations described (Pantosti *et al.* 1993; Westaway 1993; Hippolyte *et al.* 1994). Palaeomagnetic data collected in Upper Pliocene and Lower Pleistocene clayey units of some intramontane (piggy-back) basins and in the foredeep of the southern Apennines have revealed strong counter-clockwise rotations (20°–25°), suggesting that thrusting was still active after the Early Pleistocene (Sagnotti 1992; Scheepers, Langereis & Hilgen 1993).

Considering all the available stress data, we conclude that the entire southern Apenninic belt, from the Tyrrhenian to the Adriatic, is presently characterized by a regional stress field with a common NE-trending, horizontal σ_3, and σ_1 vertical in the belt and possibly horizontal (NW–SE) in the foredeep. This general conclusion is supported by the comparison of different stress data presented in this paper. The results of mesostructural analyses in Middle–Late Pleistocene outcrops (Rebai *et al.* 1992; Hippolyte *et al.* 1994) are summarized in the histograms of Fig. 6 [σ_3 directions (c), S_{hmin} distributions from breakouts (a) and T-axes from focal mechanisms (b)]. The three distributions are surprisingly similar, all showing a clear prevalence of directions between NNE and ENE. The widespread spatial and depth distribution of the different data considered (near-surface for mesostructural data, 0–6 km depth for breakouts, ≈ 3–20 km for earthquake focal mechanisms) suggests that the process of NE extension affects the entire brittle crust, in a broad region spanning from the Tyrrhenian offshore to the Adriatic foredeep, and affects both the 'upper plate' (the crustal stack above the subducted Adriatic lithosphere) and the underthrust Adria plate, although very few data were collected from this plate.

From our data we cannot assess if the hypothesized stress change at 0.7 Ma really did occur, as both breakouts and focal mechanisms are indicators of the present-day stress. However, the finding that not only the belt but also the Adriatic foredeep and to some extent the foreland are affected by a similar NE-directed extension, with no evidence of contemporaneous shortening perpendicular to the mountain belt (as there was until the Lower–Middle Pleistocene), reinforces the hypothesis of a recent change in the stress field. Similar recent (0.4–0.6 Ma) stress-field changes have been documented in other regions of extensional tectonics, such as the central East African rift system (Bosworth, Strecker & Blisniuk 1992). An even more dramatic and recent change in the stress field was proposed for Fennoscandia in Holocene times (Gregersen 1992).

Understanding the forces that are responsible for the observed present-day stress field is a difficult task, since many geological processes are active simultaneously at present in the Italian region. These include the general NNW–SSE convergence between the African and Eurasian plates, evident from global plate-motion studies (e.g. De Mets *et al.* 1990), the subduction of Ionian lithosphere beneath the Calabrian arc (and possibly of Adriatic continental lithosphere beneath the Apennines), and the related opening of the Tyrrhenian basin. Other forces, some of which are determined by these main processes, also need to be taken into account. These are mainly related to strong variations in crustal thickness, lithospheric thickness, density and strength between the different blocks that interact in the region.

It is difficult to evaluate which of the processes described prevail in determining the present-day stress field. This is also due to a poor knowledge of some of the parameters involved in such processes, for instance the geometry of the boundaries between the different blocks/microplates involved (for example the southern termination of the Adriatic plate and its connection with the African plate), the nature, age and extent of the subducting Ionian lithosphere, the relationship between Ionian oceanic and Adriatic continental lithosphere subducted beneath the Apennines, and the thicknesses and differential strengths of the Adriatic and Tyrrhenian crust and lithosphere.

In the following discussion, we review the main sources of stress in the region, trying to qualitatively evaluate for each what their contribution is to the stress field, at least in terms

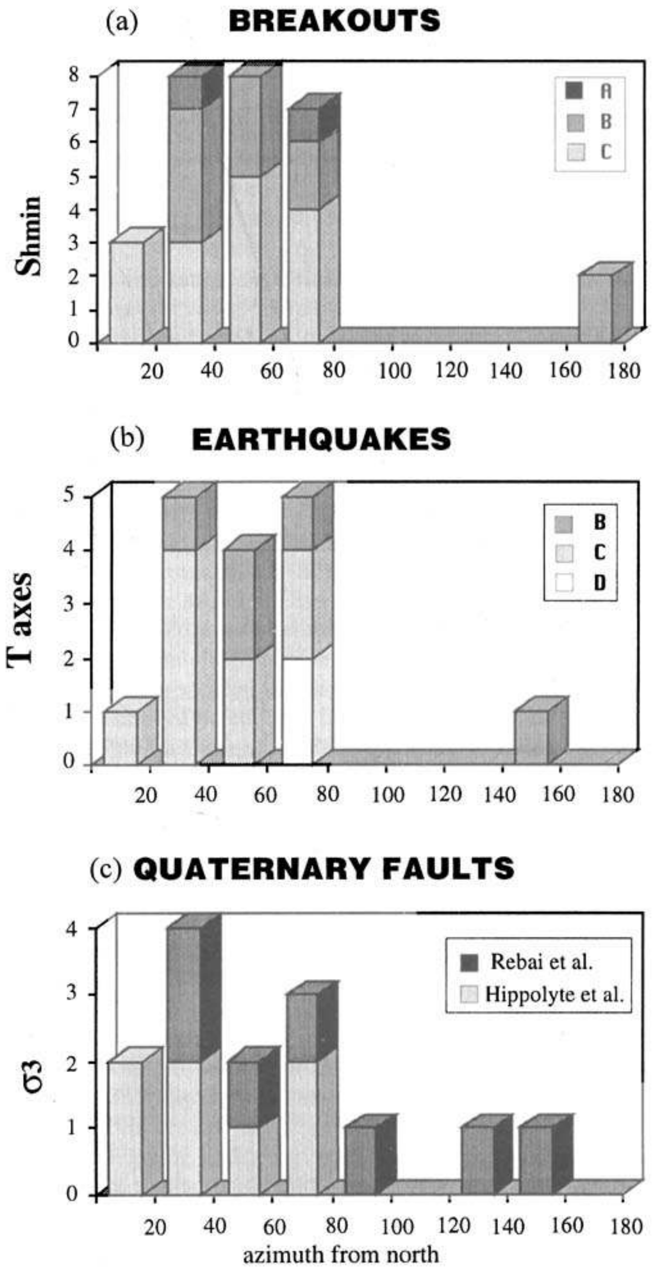

Figure 6. a) Histogram of reliable S_{hmin} orientations for breakout data; (b) histogram of reliable T-axis orientations for earthquakes (see references in Table 4; (c) histogram of reliable S_{hmin} (or σ_3) orientations for mesostructural indicators (see references in Table 3).

of horizontal stress directions, and where possible in terms of the stress regime.

Europe–Africa convergence and the Adria microplate

Global plate-motion studies show that the two major plates, namely Africa and Eurasia, are presently converging at a slow rate (5–8 mm year^{-1}) in a northwest direction (NUVEL-1, De Mets *et al.* 1990). NUVEL-1 predicts N45°W convergence near Gibraltar, and N20°W convergence near Sicily (Argus *et al.* 1989). Although there are other proposed directions of convergence between Africa and western Europe (NE–SW, Mantovani *et al.* 1996), we rely more on NUVEL-1 because the solution proposed by Mantovani *et al.* implies a plate boundary with sinistral motion dividing western from eastern Europe that does not appear to be supported by geological and geophysical evidence (see e.g. Müller *et al.* 1992).

Even if the NNW trend of convergence between Africa and Eurasia is consistent with a direction of S_{hmin} around N70°E, thus close to what is observed in the Apennines, we do not believe that the convergence force alone can explain the NE S_{hmin} detected throughout the Italian Peninsula, both because the African plate and the Adriatic microplate are probably not directly connected to each other, and because other processes certainly affect the stress field (see below). Finetti (1982), among many others, mapped the complex mosaic of microplates of this region, showing that the Adriatic continental plate terminates to the south on the transcurrent Kephalonia fault and is connected in the southwest to the eastern Ionian sea through a region of old (Mesozoic) crustal thinning. Anderson & Jackson (1987a), studying the seismotectonics of the Adriatic region, postulated the existence of a rigid and independent Adrian block that is rotating counter-clockwise with respect to Europe about a pole in the Central Alps. This hypothesis was confirmed by Ward (1994) based on VLBI data, but the very low number of vectors used (three, only one of which lies on the Apulian platform) and the inconsistency with other satellite-based directions of motions (Robbins *et al.* 1992; Noomen *et al.* 1996), suggest the use of caution in the interpretation of geodetic data in regions where the deformation rates are low, as in Italy. Noomen *et al.* (1996), investigating SLR and GPS data in the Central and Eastern Mediterranean, emphasized the prevailing northward motion of sites located on the Adriatic plate, such as Matera ($\approx$7 mm year^{-1}, in reasonable agreement with NUVEL-1), Basovizza and Lampedusa, considered as being rigidly attached to the African plate, and concluded that Adria deforms in accordance with the motion of Africa.

It should also be noted that the proposed southern termination of the Adriatic plate is not marked by any seismic activity, therefore the problem of the continuity between Africa and Adria remains open. In fact, seismic data show that the northern end of Adria is moving north below the eastern Alps and northwest below the western Alps, in agreement with the general motion of Africa towards Eurasia. Also, the only CMT fault-plane solution available for an earthquake within the Adria plate itself (see Table 4) reflects north–south compression, whereas our breakout data in the southern Adriatic suggest a horizontally isotropic stress field. If, however, the Adria plate is undergoing N–S compression, the observed direction of S_{hmin} of N64°E in the Apulian foreland could be interpreted as the interaction between the N40°–50°E S_{hmin} typical of the belt and the E–W direction of S_{hmin} associated with the N–S (or NNW–SSE) plate convergence.

Therefore, even if a conclusive answer on the role of the Adriatic microplate or promontory cannot be provided yet, we believe that the widespread NE extension of the southern Apennines is not directly related to the northward pushing of Adria against Eurasia. We hope that in the future geodetic data will demonstrate whether Adria is really rotating counterclockwise about a pole in northern Italy, as suggested by Anderson & Jackson (1987a). This process could cause extension on the Tyrrhenian side (including the Apennine belt) and compression on the Dinarides/Hellenides front.

An interesting attempt to model the recent evolution of the Italian Peninsula was recently performed by Faccenna *et al.* (1996), using an experimental approach. This work showed that in the region surrounding the southern Tyrrhenian (i.e. the southern Apennines), the E–W to NE–SW extension cannot be generated only by the northward indentation of the African plate, but rather by the combined effect of this and the retreating of the Adria–Ionian lithosphere, and to a lesser extent by the gravitational collapse of a thickened post-collisional wedge. Finite-element models computed by Bassi & Sabadini (1994) also emphasized the importance of subduction-related forces in explaining the present-day stress (see below).

The roll-back of the Adriatic lithosphere subducted beneath the Apennines would cause extension in the back-arc and compression at the outer front, as in the models of Whittaker *et al.* (1992). However, as previously discussed, the coexistence of contemporaneous compression and extension in the southern Apennines is ruled out by the breakout data presented here, which show the same directions of S_{hmin} in the belt and in the foredeep. This mechanism is probably applicable to the past (Upper Miocene–Pliocene) evolution of this area, but is no longer active today. If this is true, and if we accept the hypothesis of the stress change at 0.7 Ma, we must also accept that something in the subduction process changed at that time. A viable candidate at this point is the proposed slab detachment, which will be discussed in the next section. Alternatively, a change from a locked to an unlocked subduction fault, or subduction of buoyant continental lithosphere might have produced such a change.

Tyrrhenian (and Apenninic?) subduction

The presently active (i.e. geophysically documented) subduction in Southern Italy is limited to a narrow (about 200 km wide) zone beneath the Calabrian arc, where seismicity (e.g. McKenzie 1972; Gasparini *et al.* 1982; Anderson & Jackson 1987b; Frepoli *et al.* 1996) and seismic tomography (Spakman, van der Lee & van der Hilst 1993; Amato *et al.* 1993; Selvaggi & Chiarabba 1995) nicely delineate the seismic high-velocity slab dipping to the northwest. The steep dip of the slab (around 70°) and the geological evolution of the region (Malinverno & Ryan 1986) suggest that the Calabrian arc has been and is still retreating, causing the opening of the Southern Tyrrhenian basin (Kastens *et al.* 1988).

To the north of the Calabrian arc, beneath the southern Apennines, the westward subduction of continental Adriatic lithosphere is much less evident, because no intermediate earthquakes are located beneath the southern Apennines (Selvaggi & Amato 1992), and no clear high-velocity anomalies are visible from seismic tomography. Only at depths of about 300–400 km does the Tyrrhenian coastal region of the southern Apennines (around latitude 41°N) show a clear high-velocity anomaly associated with deep seismicity (Amato *et al.* 1993; Spakman *et al.* 1993), which reflects the remnant of a subducted slab. It is not clear whether this is related to the NW-dipping Ionian oceanic-like lithospheric slab of the Calabrian arc, or to a continental Adriatic slab beneath the Apennines. Amato *et al.* (1993) proposed that the region between the central Apennines and the Calabrian arc (the southern Apennines) is a 'slab window', generated by the subduction of an irregularly shaped Ionian/Adriatic lithosphere, bounded to the northwest by the 'shallow' (down to 200–250 km) northern Apenninic subduction and to the south by the 'deep' (down to 400–500 km) Calabrian subduction. The slab window could result from the subduction of a passive margin in which two residual oceanic fragments are separated by a region of continental lithosphere.

Numerical models of the subduction process in the Tyrrhenian region have been constructed by Bassi & Sabadini (1994) to evaluate the relative importance of subduction with respect to the N–S convergence between Africa and Eurasia. They concluded that the subduction process is fundamental in explaining the modern stress and strain field. The 2-D horizontal model of Bassi & Sabadini (1994) reproduced the NE extension in the southern Apennines, imposing a trench-suction force all around southern Italy (from the central Apennines to Sicily), implicitly assuming the continuity of the subducting slab throughout the arc, which is not demonstrated. Moreover, in this 'trench-suction' model, a NE-oriented compression was predicted along the Apenninic foredeep. Even if this agrees with the interpolated stress map compiled by Rebai *et al.* (1992) and with the 'recent and present-day' stress map of Philip (1987), the breakout data demonstrate that the NE-oriented compression is no longer active. Notwithstanding this discrepancy, which certainly needs to be considered in future modelling, we believe that the Ionian–Adriatic subduction plays a fundamental role in the present state of stress, as already suggested by Bassi & Sabadini (1994).

Evidence of subduction of Adriatic crust beneath the Apennines comes from geological observations, mostly based on the observed westward flexure of the Adriatic crust beneath the thrust belt. Flexural stresses induced by loads on or within an elastic lithosphere can be as large as several hundred megapascals (Zoback 1992). Royden *et al.* (1987) pointed out that the flexure of Pliocene sediments beneath the Apennines cannot be explained by the sole topographic load, but rather is due to the subsurface load of a dense subducted slab in the upper mantle (Royden 1993). Kruse & Royden (1994) also argued that the observed unbending of the Adriatic lithosphere beneath the northern Apennines after the Early Pleistocene is due to the diminution of forces acting on the slab at depth. This has been interpreted by Hippolyte *et al.* (1995) as proof in favour of slab detachment beneath this region. The hypothesis of slab detachment, advanced by Spakman *et al.* (1993) based on seismic tomography, has been used by Westaway (1993) to explain the observed uplift of Calabria (at 1 mm year^{-1}) and by Hippolyte *et al.* (1994) to explain the recent (post-Middle Pleistocene) extension of the southern Apennines. These authors qualitatively argued that the isostatic rebound of the detached lithosphere would generate the uplift (see Fig. 8 in Hippolyte *et al.* 1994). Beneath Calabria, recent tomographic studies (Amato *et al.* 1993; Selvaggi & Chiarabba 1995) and accurate locations of recent earthquakes (Frepoli *et al.* 1996) suggest that the slab is continuous down to about 350 km, without any evident detachment. Moreover, finite-element modelling of the Tyrrhenian subduction by Giunchi *et al.* (1996) showed that the uplift can be explained by the slab retreat process and that a detached slab would instead cause subsidence above the subduction hinge, due to the downward traction of the dense sinking slab. As mentioned above, the presence of subducted lithosphere beneath the southern Apennines is even more uncertain, at least in the uppermost mantle.

As a speculation, we may hypothesize that the subducted oceanic lithosphere (today located from seismic tomography at 300–400 km depth beneath the Tyrrhenian coastal region, see Amato *et al.* 1993) detached from the Adriatic continental lithosphere several million years ago, then continued to sink into the asthenosphere, causing first a downward traction on the Apenninic prism. Afterwards, when the isostatic rebound of the buoyant Adriatic continental lithosphere became larger than the force exerted by the dense sinking slab, the region could start to uplift, and this happened during the Quaternary, probably around 0.7 Ma. This mechanism would imply a very fast descent rate for the detached sinking slab, on the order of several centimetres per year, and appears therefore unlikely. An alternative mechanism is that the deep (300–400 km) oceanic lithosphere is not detached and is pulling down the Adriatic continental lithosphere, characterized by an absence of seismicity and no clear high-velocity anomaly [a weak (+2 per cent) discontinuous positive anomaly is actually visible below ≈ 200 km from the tomographic images of Amato *et al.* (1993)]. To explain this, we can infer that the subducted continental lithosphere has been conductively heated during its descent in the asthenosphere, as suggested by Kruse & Royden (1994), causing the diminution of downward-directed forces on it, and the subsequent unbending of the upper portion of the slab and the recent uplift of the region above the slab. An alternative explanation of the Calabria uplift (Sengor 1993) implies underplating of buoyant material above the subducting oceanic, or even attenuated continental lithosphere, both being negatively buoyant.

Other sources of stress in the study region are those linked with lateral variations in crustal and lithospheric thicknesses and rock strength. Numerous papers have demonstrated that density anomalies within or just beneath the lithosphere can produce stresses capable of influencing the tectonic style (see e.g. Fleitout & Froidevaux 1982; Zoback 1992 and references therein). In general, negative density anomalies, such as crustal thickening and lithospheric thinning, generate extensional stresses, whereas positive density anomalies produce compressional stresses. Good examples of stress rotations in regions of lithospheric thinning, such as the East African rift, and of lithospheric thickening, such as in the Colorado Plateau or in the Western Alps, were summarized by Zoback (1992). In southern Italy, strong variations in both crustal and lithospheric thicknesses are present. Both the crust and the lithosphere are two to four times thicker in the Adriatic than in the Tyrrhenian (Suhadolc & Panza 1989). The boundary between these two very different regions corresponds to the Apenninic belt, thus additional sources of stress, besides those described above, can modify the present stress field in this region. Future modelling of this region should also take into account these large variations in the physical properties of the Adriatic and Tyrrhenian lithosphere and their effect on the boundary region (the Apennines) where most of the (seismic) deformation takes place.

CONCLUSIONS

The present-day stress field in southern peninsular Italy is dominated by a NE-oriented minimum compressive stress, S_{hmin}. This is observed in the Tyrrhenian coastal region, where other directions are found, probably due to local sources, and is very clear in the belt where stress directions inferred from breakouts, focal mechanisms of earthquakes and recent geological data all indicate a normal-faulting stress regime with a very evident NE direction of extension, recorded at all the sampled depths, 0–20 km, 0–6 km and ≈ 0 km, respectively. From the comparisons among these stress indicators, we emphasize the importance of breakout data for two reasons: first, breakouts provide information on the stress field in aseismic regions, such as the foredeep of the southern Apennines; and second, although breakouts sample only the upper 5–6 km of the crust, they are the only real measures of present-day stress, because earthquakes can occur on pre-existing faults with low shear strength, and therefore even at high angles to the regional stress. Also, inversion of microtectonic data can fail if the stress field has recently changed, and tectonic structures related to active tectonics are not so evident in regions such as Italy with low strain rates (a few millimetres per year). Of course, comparisons among all the available data, where possible, are the most effective way to constrain the stress directions and stress regime.

In the study region, the breakout data indicate that the stress field has changed recently, probably around 0.7 Ma. This is demonstrated by the age of the most recent documented compressional features (Lower to Middle Pleistocene), and agrees with the observation that active (seismogenic) faults are new. Also, the foredeep and the most internal (Apulian) foreland region show a similar direction of S_{hmin}, but rotated by $\approx 20°$. This could be due to the interaction of NE extension of the Apenninic belt and the hypothesized N–S to NNW–SSE internal compression of Adria (a consequence of the N–S convergence between Africa and Europe, if Africa and Adria are somehow connected), and/or the flexing of the Adriatic lithosphere beneath the belt. In any case, the breakout results rule out the hypothesis of a still-active compressional thrust front in the southern Apenninic foredeep, in contrast with inferences from previous stress compilations. In the foredeep and foreland, we cannot assess whether the ENE-trending S_{hmin} is connected with a normal-faulting or a strike-slip stress regime, due to few earthquakes occurring in the foreland.

It seems that a correlation exists between stress directions observed at shallow depths and upper-mantle structures, suggesting that deep processes control the tectonic evolution in the brittle crust. In the southern Apennines, where there is no clear evidence of an actively subducting slab from either earthquake distributions or seismic tomography, in contrast with the northern Apenninic and Calabrian arcs, we speculate that the subduction of buoyant Adriatic continental lithosphere, possibly detached from a previously subducted oceanic-like slab, can determine the present state of stress.

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