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# THE ACTIVE CRUSTAL STRESS: METHODS AND RESULTS IN ITALY*

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RIASSUNTO - *Il campo di stress attivo nella crosta: metodi e risultati in Italia* - Il Quaternario *Italian Journal of Quaternary Sciences* , **10**(2), 1997, 313-320 - In questo lavoro vengono presentati i risultati relativi a misure di *breakout* in pozzi profondi e dati di terremoti di bassa-media magnitudo, analizzati negli ultimi cinque anni in collaborazione con diversi ricercatori dell'Istituto Nazionale di Geofisica (ING). L'analisi di tali dati permette di determinare il campo dello sforzo attivo, direzione degli assi ($S_{h_{min}}$ e $S_{H_{max}}$ dai *breakout,* e assi T e P dai meccanismi focali) e la disposizione di questi nello spazio, lungo l'intervallo crostale compreso tra 0 e 15-20 km. Per ottenere un quadro regionale dell'andamento del campo degli sforzi sono stati presi in considerazione circa 200 pozzi, tra 0.5 e 7 km di profondità, e 300 terremoti (2.5<Md<5) avvenuti tra il 1988 e il 1995. Il confronto tra dati di *breakout* e terremoti, nonché l'integrazione di altri dati geologici e geofisici ha permesso di definire, anche se ancora non completamente per l'intero territorio, aree caratterizzate da regimi ed orientazioni dello sforzo coerenti al loro interno, pur mostrando variazioni tra regioni contigue. Lungo la penisola italiana coesistono regimi e direzioni di sforzo differenti: la parte più settentrionale, compresa tra 43° e 44.5° di latitudine, lungo i fronti dei *thrust* più esterni, è caratterizzata da massimi sforzi orizzontali in direzione circa NE-SW (con regime di sforzo compressivo e trascorrente). Dal 43° di latitudine, procedendo verso l'Appennino meridionale, sia in catena che lungo il margine costiero tirrenico che lungo l'avanfossa il regime di sforzo attuale è prevalentemente distensivo con assi di estensione mediamente NE-SW. In Sicilia si individuano differenze tra l'area di avampaese e l'area di avanfossa-catena: la prima è caratterizzata da una ben definita direzione di $S_{H_{max}}$ NNW-SSE, la seconda mostra più orientazioni, sia in regime compressivo che distensivo, con direzioni di $S_{h_{min}}$ circa NW-SE e NE-SW. In questo lavoro viene presentata solo una sintesi dei risultati raggiunti finora e il confronto tra campo dello sforzo così ottenuto e tettonica recente in Italia. Il *dataset* completo è stato in parte pubblicato in diversi lavori. Per una visione completa dei dati di *breakout* (profondità dei pozzi, litologia attraversata, lunghezza della zona di *breakout,* errore associato) e dei dati di sismicità presi in considerazione (magnitudo, profondità degli eventi sismici, meccanismo focale, errore associato) si rimanda ai lavori: Montone *et al.* (Geophys. Res. Lett., **22**(14), 1995), Amato & Montone (Geophys. J. Int., **130**, 1997), Frepoli & Amato (Geophys. J. Int., **130**, 1997 e Geophys. J. Int., 1998, sottoposto), Montone *et al.* (Ann. di Geofisica, **40**(3), 1997), Mariucci *et al.* (Tectonics, 1997 sottoposto).

Keywords: Active stress, breakout, seismicity, Italy
Parole chiave: Campo di stress attivo, breakout, sismicità, Italia

## 1. INTRODUCTION

This paper summarizes methods and results, most of which already published, obtained by a working group at Istituto Nazionale di Geofisica (ING) in the last five years, and relative to active crustal stress as determined by borehole breakout analysis and seismicity data. To date, about 200 deep wells (0.5-7 km depth) and 300 crustal earthquakes (2.5<Md<5) occurred between 1988 and 1995 in Italy, were analyzed in order to determine the active stress field in the Italian crust.

The present-day stress in Italy is determined by several contemporaneous tectonic processes, which have been active in the last millions of years, although there is evidence that major stress changes have occurred during the Quaternary.

The geological and tectonic setting of the Apennines consists of two principal subduction/collisional arc structures developed in post-Tortonian times (Patacca & Scandone, 1987) — the northern and the southern Apennines arcs separated by a narrow area where the dominant structures are N-S trending. These N-S trending structures, well constrained by geophysical and geological data (Bouguer anomalies, trend of structures and isobaths of the Pliocene base) separates two different areas, the central Apennines and the northern Apennines, characterized in the past (Tortonian-Early Pliocene) by different velocities of the propagating thrust fronts (Cipollari & Cosentino, 1995; Patacca *et al.*, 1992). The chain is characterized by a fold and thrust belt made up of Meso-Cenozoic units deposited in different paleogeographical domains, determined by compressional tectonics that was migrating towards E and NE onto the foreland, from Oligocene (west side) to Pliocene-Pleistocene times (east side). To the east a continuos foredeep, from the Po plain to Sicily, is formed by a thick sequence of Plio-Pleistocene prevalent clay and sand deposits. From geological and geophysical data (Gasparini *et al.*, 1985; Pondrelli *et al.*, 1995; Montone *et al.*, 1997) the area of active compression is now confined to the external northern Apennines and to the outer Calabrian arc (Vai, 1987; Patacca & Scandone, 1987). The remaining part of the Italian peninsula seems to be dominated by active extensional tectonics, as testified also by recent strong earthquakes (Pondrelli *et al.*, 1995).

The Calabrian arc was affected by intense Quaternary tectonics represented by normal faults, parallel to the orientation of the arc, especially along the Tyrrhenian

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(*) Relazione ad invito/*Invited paper*

side. The activity of these faults seems to be controlled by an ESE extension (Catalano *et al.*, 1993). Since Late Miocene, the Calabrian region has mainly been characterized by extensional tectonics with the formation, along the coastal margin, of NW elongated marine basins (Valensise *et al.*, 1993).

Sicily was characterized by compressional tectonics from Early Miocene to Middle Pliocene, with maximum shortening toward the south; only in Plio-Pleistocene times it was affected by extensional tectonics with normal faults and strong uplifting movements.

The knowledge of the present-day stress field in Italy is needed to better understand active tectonic processes and to assist in the assessment of seismic hazard in Italy (Zoback, 1993). Since 1992 ING has collected and analyzed stress data from borehole breakouts in deep oil and geothermal wells, in a cooperative research with AGIP S.p.A. and ENEL S.p.A. (National Oil and Electricity Authority, respectively; Amato *et al.*, 1995; Montone *et al.*, 1995). Most of the deep wells are located along the foredeep and some of them in the southern Apenninic belt; conversely, seismicity is more concentrated along the belt and almost absent along the foredeep.

Present-day stress information was compared to the seismicity pattern in Italy, particularly to small-medium magnitude earthquakes (Frepoli & Amato, 1997; 1998), and other geological and geophysical data.

In this paper, we review all the stress data analyzed to date, and compare the results obtained so far to the most recent tectonic features inferred from geological mapping and neotectonic analyses.

The comparison between these two data sets allows us to infer which recently active faults are possibly still active today, and whether the stress field may in some regions have changed in very recent times, so that the active faults may not have a clear surface expression.

## 2. METHODOLOGY

Breakouts are caused by conjugate shear failures that develop in two opposite sides of the borehole wall, when a well is drilled in an anisotropic stress field (Fig. 1) (Bell & Gough, 1983; Plumb & Hickmann, 1985; Zoback, 1992). The axis of elongation is aligned with the minimum horizontal principal stress ($S_{h_{min}}$) directions and, thus, perpendicular to the maximum horizontal stress ($S_{H_{max}}$). To measure the azimuth of breakout zones we used four-arm caliper dipmeter logs provided by AGIP and ENEL. The criteria to recognize a breakout zone on a dipmeter log are summarized in Plumb & Hickmann (1985): a) tool rotation must cease in a breakout zone); b) enlargement of one caliper with respect to the other one; c) hole azimuth must be different from the breakout azimuth by more than 10°; d) hole deviation from the vertical (not more than 15° and not less than 0.5°).

Since no shear stresses can exist in the plane of the Earth's surface, one of the principal stresses in the upper crust should be oriented approximately perpendicular to it (Anderson, 1951). In this work results and interpretations are based on this assumption (McGarr & Gay, 1978; Zoback, 1992). In most cases this is supported by the inversion of focal mechanisms with stress axes generally within 20° from the vertical.

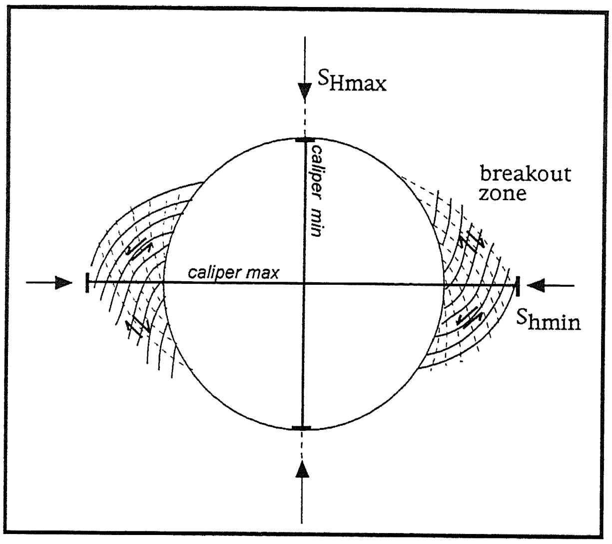

Fig. 1 - Horizontal borehole section: anisotropic stress-induced breakouts geometry (lunate shape). Failures of borehole wall represent the area of breakouts. Modified after Plumb & Hickmann, 1985.

*Sezione orizzontale di una perforazione: la formazione di una zona di* breakout *è indotta dalle fratture di taglio che si creano lungo la parete del pozzo sotto l'azione di un campo di* stress *anisotropo. Modificata da Plumb & Hickmann, 1985.*

According to the criteria suggested by Zoback (1992) we assigned a quality factor for each well, from A (the best quality) to D (worst quality, not reliable stress indicators). Figure 2 shows all breakout results highlighted by different thick lines.

Earthquake locations of the referred to in this study were obtained by Frepoli & Amato (1997; 1998) with the computer program *Hypoinverse* (Klein, 1989) using a gradient velocity structure. Focal solutions were determined with the program *Fpfit* (Reasenberg & Oppenheimer, 1985).

## 3. RESULTS

In this paper we present only the results of the breakout and seismicity analyses. All information concerning borehole breakout data (depth of the wells, breakouts' length, crossed lithology, discussion on data quality) and the analyzed earthquakes (hypocentral depth, magnitude, focal mechanism and discussion of potential errors) are partially published in Montone *et al.* (1995; 1997), Amato & Montone (1997), Frepoli & Amato (1997; 1998), and Mariucci *et al.* (1997).

Breakout data have been grouped according to their internal consistency in large regions of Italy. The mean stress directions computed by averaging a great number of $S_{hmin}$, can be regarded as the regional directions of the horizontal stress in the main Italian provinces (Fig. 4). Smaller scale deviations, visible from the dispersion of mean values, are seen as due to local effects and will not be discussed here.

The breakout analysis for the wells located in the

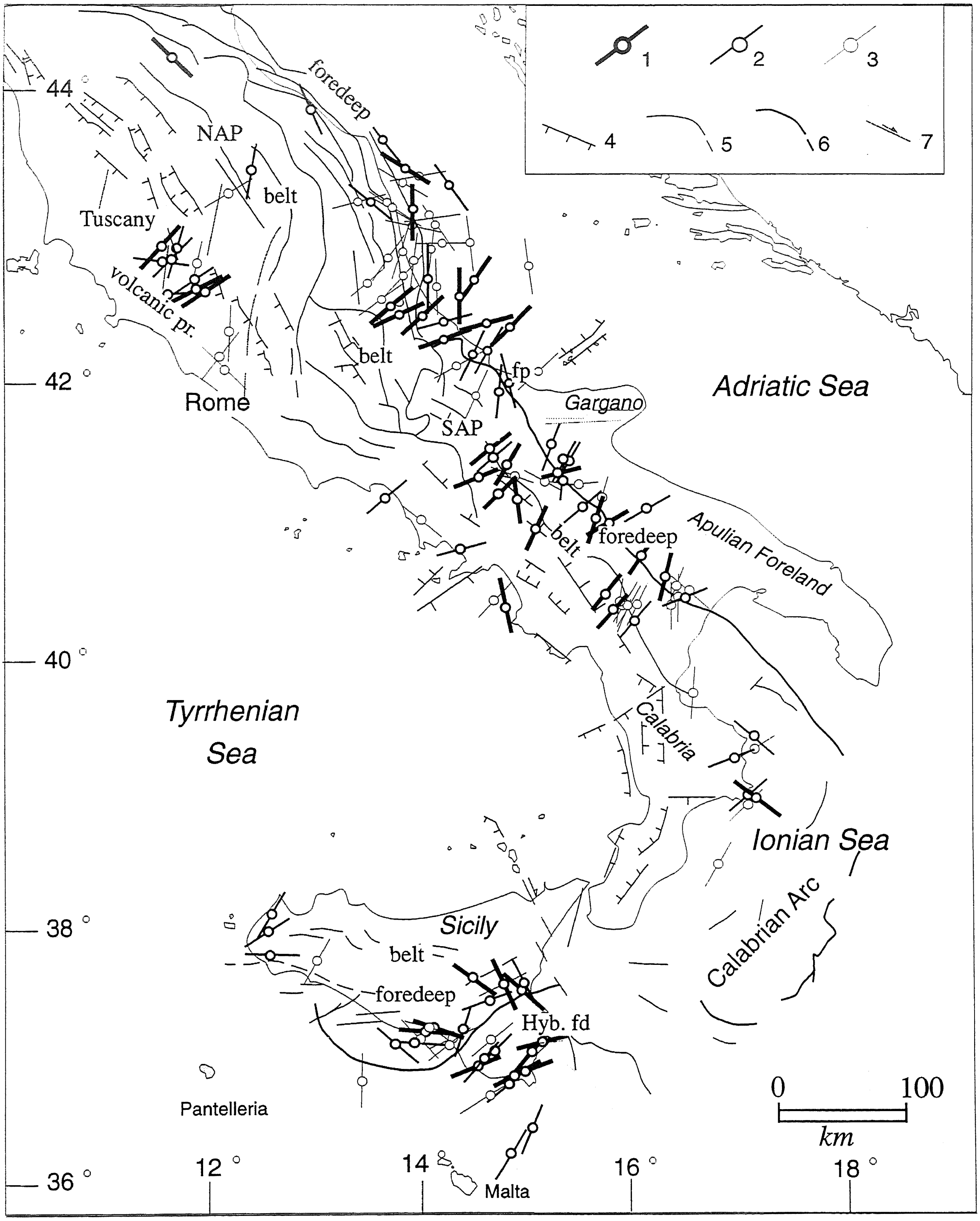

Fig. 2 - $S_{hmin}$ directions from breakout analysis according to data quality. 1) 'A' and 'B' quality (the best) ; 2) 'C' quality; 3) 'D' quality (the worst); tectonics simplified from Bigi *et al.*, 1990: 4) normal faults; 5) major overthrusts of the Apennines; 6) front of the "plastic" allochthonous sheet; 7) strike-slip and undetermined faults. NAP and SAP = northern and southern Apennines; fp = foredeep; Hyb. fd = Hyblean foreland. Modified from Montone *et al.*, 1997.

*Direzioni di* $S_{hmin}$ *ottenute dall'analisi di* breakout *nelle perforazioni profonde in funzione del valore di qualità attribuito al risultato del pozzo. 1) qualità 'A' e 'B' (migliore) ; 2) qualità 'C'; 3) qualità 'D' (peggiore); tettonica semplificata da Bigi* et al., *1990: 4) faglie normali; 5) principali* thrust; *6) fronte delle coperture alloctone; 7) faglie trascorrenti e indeterminate. NAP e SAP = Appennino settentrionale e meridionale; fp = avanfossa; Hyb. fd = avampaese Ibleo. Modificata da Montone* et al., *1997.*

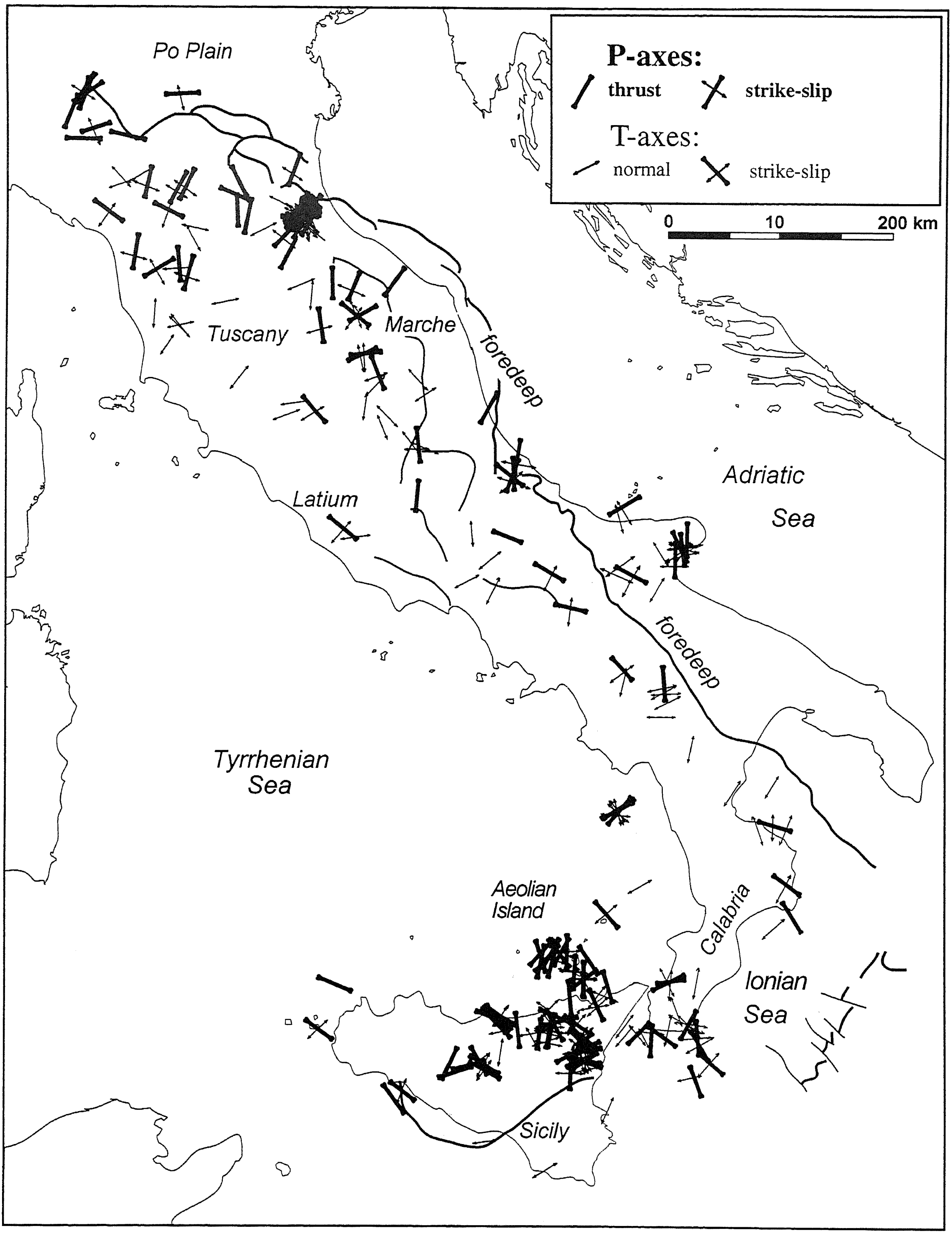

Fig. 3 - P and T-axes distribution of thrust, normal and strike-slip fault-plane solutions in the period 1988-1995. Modified from Montone *et al.*, 1997.

*Distribuzione degli assi P e T dei meccanismi focali per il periodo 1988-1995. Modificata da Montone* et al., *1997.*

northern sector of the Po plain-Adriatic foredeep zone (about north of lat. 43°N), shows predominantly NW oriented $S_{h_{min}}$ (in the range N24°W - N60°W) (Mariucci *et al.*, 1997; Montone *et al.*, 1997). This result is consistent with the focal mechanisms of earthquakes in this area, which indicate mostly thrust fault solutions with NE-SW oriented P-axes. From the seismicity analysis, the most important result is the clear separation between a large area (Fig. 3), characterized by normal (and subordinately strike-slip) faulting, and another one in which reverse (and strike-slip) faulting solutions prevail (Frepoli & Amato, 1997). The first area includes the inner (western) part of the belt and the Tyrrhenian coastal region, whereas the second corresponds to the outer thrust front area.

Near 43°N we detected rotations in the direction of $S_{hmin}$, from NW-SE to NE-SW with some wells yielding almost N-S and E-W trending $S_{hmin}$ orientations (even if quality is low). These different orientations could be due to a "transition" area between active transpression, to the north, and widespread active extension, toward the south.

From lat. 43°N to the Gargano Promontory (Fig. 2), the breakout analysis indicates NE-SW-oriented $S_{hmin}$ (ranging between N22°E and N55°E), in continuity with the stress directions observed in Southern Italy (Amato & Montone, 1997; Mariucci *et al.*, 1997, see below).

An ca. NE orientation of breakouts, similar to that observed in the belt and south of 43° lat. N in the foredeep region, was recognized in the Tyrrhenian back-arc region of central Italy, around the Quaternary volcanoes of Latium and southern Tuscany (Fig. 2). There, a NE to ENE $S_{hmin}$ was observed, in agreement with the inversion of focal mechanisms that indicate a NE-SW $\sigma_3$ direction (Montone *et al.*, 1995).

The same direction found south of 43°lat. N is present in the southern Apennines (Amato *et al.*, 1995; Amato & Montone, 1997). A NE-SW $S_{hmin}$ is evident throughout the southern peninsula, with a N40°-50°E $S_{hmin}$, in agreement with the seismic deformation inferred from large earthquakes (Fig. 5). A bimodal distribution is detected in the southern Apenninic foredeep with a NE-trending $S_{hmin}$, and a secondary pick which is N60°-70°E oriented, and is relative to a deep well in the Apulia foreland and to a few wells in the foredeep (Figg. 2, 4). Seismicity in the foredeep region consists of a few, mostly strike-slip earthquakes that suggest horizontal $S_{Hmax}$ and $S_{hmin}$, and a nearly vertical $\sigma_2$ (Figg. 3, 5) (Frepoli & Amato, 1998). In the Adriatic foreland no elongations were found in the few wells located off-shore the southern Adriatic Sea: this result could indicate the presence of isotropic horizontal stress or may be due relatively shallow wells drilled in unconsolidates sediments. No reverse solutions of earthquakes with 2.5<M<5 were determined in this area from 1988 to 1995.

In the southern Apennines, analysis of 2.5<Md<5 earthquakes (Frepoli & Amato, 1998), also indicates extensional tectonism with NE $S_{hmin}$ direction (perpendicular to the belt), in close agreement with the $S_{hmin}$ orientation inferred from the breakout analysis (Fig. 4).

Analysis of eight wells in the Ionian Calabria region yielded large scatter in breakout directions, even in closely-spaced wells (Fig. 2). In the northern sector we found a ~NS oriented $S_{hmin}$ (Fig. 2), in agreement with focal mechanisms (Fig. 4). The central group exhibits two $S_{hmin}$ directions, perpendicular to each other: roughly NW-SE and NE-SW oriented (Fig. 2). The different $S_{hmin}$ directions observed in this area may be related to its proximity to the transition between the Calabria mainland, where extensional tectonics and uplift dominates, and a regional compression area (more to the east), as shown from geological data (Ghisetti *et al.*, 1982; Moussat *et al.*, 1986). Alternatively, perpendicular breakout orientations may indicate that one direction is a true breakout direction, whereas the other one is due to drilling-induced hydrofractures enlarged by subsequent drilling and mud circulation.

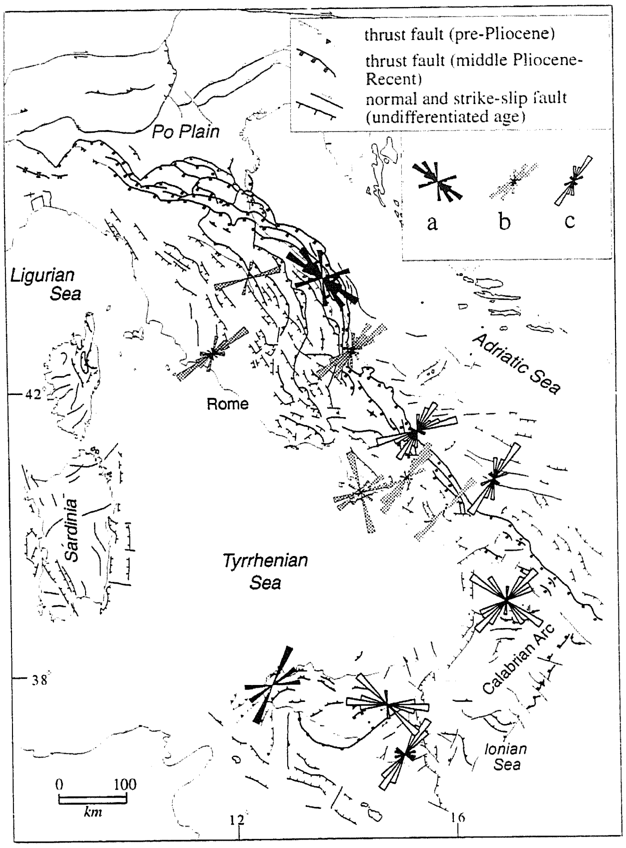

Fig. 4 - $S_{hmin}$ rose diagrams of breakout data grouped according to their internal consistency. Rose diagrams were computed using $S_{hmin}$ mean values. a: $S_{hmin}$ relative to compressional-transpressional stress regime; b: $S_{hmin}$ relative to extensional stress regime; c: $S_{hmin}$ relative to an unknown stress regime. Tectonics from Bigi *et al.*, 1990.

*Diagrammi a rosa dell'orientazione dell'*$S_{hmin}$ *dai dati di* breakout. *I diagrammi sono stati calcolati utilizzando le singole medie di ciascun pozzo pesate in funzione del valore di qualità attribuito. Le diverse tonalità di grigio indicano l'orientazione dell'*$S_{hmin}$ *associato al regime di* stress *compressivo/transpressivo (a), estensivo (b) e non noto (c). Tettonica da Bigi* et al., *1990.*

The foreland zone of Sicily (Hyblean area and Malta Platform) shows a consistent NE-SW $S_{hmin}$ direction (Fig. 2), while along the thrust belt margin, the stress pattern is more complex, with $S_{hmin}$ direction ranging between NE-SW (regional trend) and NW-SE (Cesaro, 1993; Ragg *et al.*, 1995).

In the southern Calabria and Messina Strait, T-axes of fault plane solutions obtained from normal/strike-slip earthquakes analysis, are rather scattered, although with a hint of rotation from a N-S trend in the north, to ~E-W near Sicily (Fig. 3) (Frepoli & Amato, 1998).

In Sicily, most of the earthquakes are concentrated in the north-eastern part of the island and have reverse faulting mechanisms with P-axes ranging between N and NW (Fig. 3). A few thrust and strike-slip solutions for events located in central and western Sicily have NW-SE oriented P-axes (Frepoli & Amato, 1998).

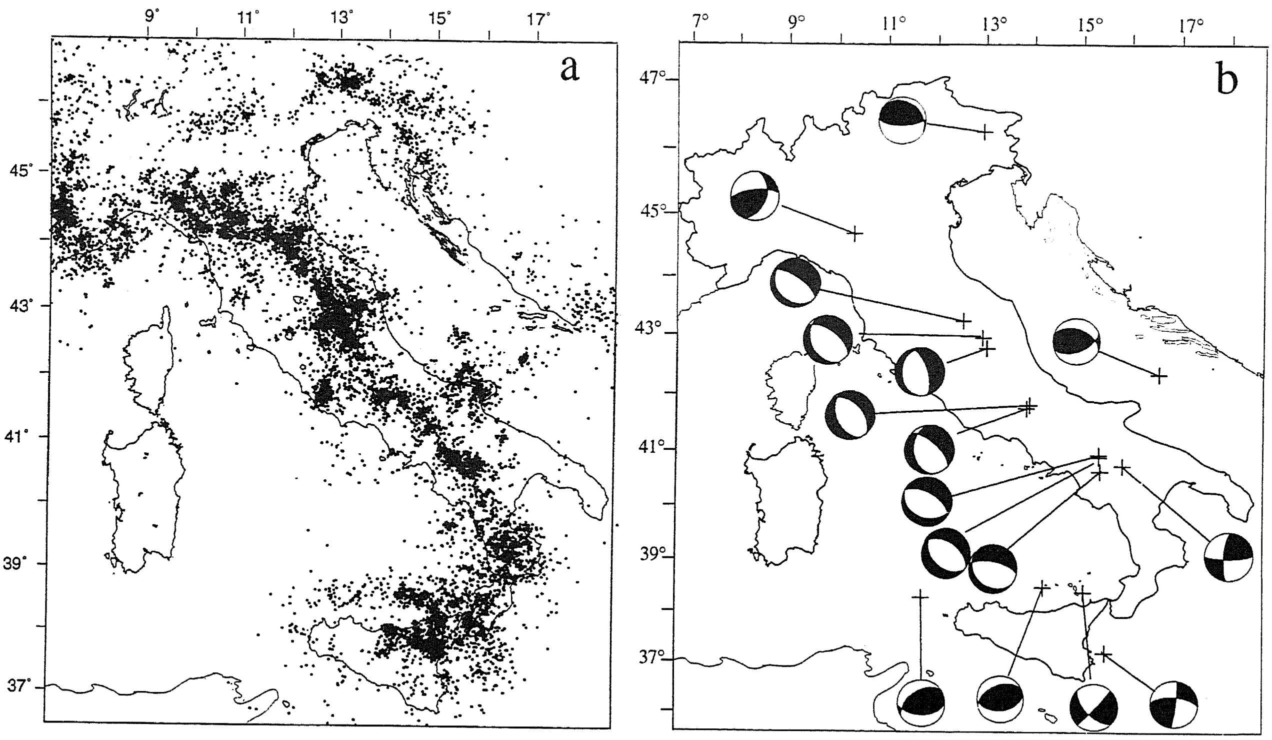

Fig. 5 - a: Epicentral map of relocated crustal earthquakes for the period 1975-1997 (Amato *et al.*, 1997, courtesy of C. Chiarabba). b: CMT focal plane solutions for the period 1976-1997. Note the extent of the extensional stress region along the entire Apenninic belt; the compressional solutions are confined in the northern area (Parma and Friuli) and along the northern margin of Sicily.

*a: Carta degli epicentri dei terremoti crostali rilocalizzati per il periodo 1975-1997 (Amato* et al., *1997, gentilmente fornita da C. Chiarabba). b: soluzioni focali CMT dal 1976 al 1997. E' evidente la preponderanza di soluzioni focali con regime di stress estensivo (lungo tutta la catena appenninica) rispetto alle soluzioni focali compressive limitate alla regione settentrionale (Parma e Friuli) e lungo il margine siciliano.*

## 4. DISCUSSION AND CONCLUSION

From the analysis of about 200 deep wells and 300 crustal earthquakes in peninsular Italy and Sicily, we found that stress orientations inferred from breakouts generally agree with those inferred from earthquake focal mechanisms (Figg. 3, 4 and 5), although they sample different depth ranges (0-7 km and 3-20 km, respectively), suggesting that no important changes occur in the stress field throughout the brittle crustal layer.

The main achievements at this stage are the following. The internal (SW) sector of the northern Apenninic arc is extending with ~ENE oriented $S_{hmin}$, while the external front appears to undergo transpression over the Adriatic foreland (~NW-SE oriented $S_{hmin}$) (Montone *et al.*, 1997). A situation similar to the one inferred for the extension direction of the belt, was recognized in the Tyrrhenian back-arc region of central Italy (Fig. 4).

Between the northern and southern Apenninic arcs, at about 43° lat. N, a rotation of the $S_{hmin}$ azimuth was detected, with directions changing by as much as 90° in the external front of the Adriatic Sea.

The entire southern Apennines chain is extending to an ~NE direction (Amato *et al.*, 1995) from the Tyrrhenian coastal region to the Apulian foreland with N40°E-N50°E $S_{hmin}$ direction. As a consequence, the Plio-Pleistocene NE-trending compression in the foredeep appears to be no longer active at the outer thrust front (Fig. 4).

In Southern Apennines, the comparison between breakout directions and T-axes of focal mechanisms of earthquakes ($3<M<7$) occurred from 1962 to 1995 (Gasparini *et al.*, 1985; Frepoli & Amato, 1997; 1998) shows surprisingly similar results in terms of angular average of all the data. The mean values of the two distributions are N44°±20° and N44°±27° for breakouts and T-axes, respectively (Montone *et al.*, 1997). In our opinion this result supports the regional significance of these data. The deviations from the mean value that we observe in some places, are probably due to "local" sources of stress (Rebai *et al.*, 1992; Zoback, 1992).

In Sicily, a NW-SE direction of $S_{Hmax}$ is evident in the Hyblean foreland whereas, a more complex pattern of stress directions is observed in the foredeep area (Cesaro, 1993; Ragg *et al.*, 1995).

Information on active stress given in this paper does not tell us where the deformation concentrates, and then where earthquakes may strike. To investigate the relationship between stress field and active deformation, a map of the present-day stress must be compared to a map of earthquakes. The map of seismicity distribution in Italy (Amato *et al.*, 1997) for the 1975-1997 events, identifies two major arcs where the seismic release is concentrated (Fig. 5a). The seismically deformed region is a belt 30 to 50 km wide, which corresponds in a first approximation to the most elevated region, whereas in the foredeep and foreland zones the seismicity is almost absent. This can be due to either very low or no deformation, or to aseismic deformation. We emphasize the importance of breakout data for these regions, because they provide the only available indications on on-going geodynamic processes. In seismically active regions, breakout data sample the upper 5-7 km of the crust, thus covering a depth interval generally not accessible by surface studies and earthquake focal mechanisms.

The integration of breakout data with seismicity pointed out the presence of both extensional and compressional (transpressional) regimes in adjacent regions of Italy. Presently, the regions characterized by horizontal $\sigma_1$ are localized along the outer thrust front of northern Apennines and in Sicily (northern margin and probably in the Hyblean foreland), (Fig. 5b). According to these data, the most recently and potentially active tectonic structures could be represented in the northern Apennines by fold and thrust preferentially oriented NW-SE. In Sicily, strong earthquakes (Fig. 5b) show activation of E-W oriented compressional structures along the northern margin, while in the Hyblean foreland the seismicity is almost absent. Here, information on active stress comes from breakout data which indicate an about NW-horizontal $S_{Hmax}$ and NE-horizontal $S_{hmin}$. This suggests that the possibly active tectonic structures are either NE-trending thrust faults or N-S (left lateral) or E-W (right lateral) strike-slip faults.

In the rest of the Apennines active extension prevails, with vertical $\sigma_1$ and NE-horizontal $\sigma_3$, well testified by recent strong earthquakes (Fig. 5b ) and borehole breakout data.

Several examples have demonstrated in the latest 20 years that the principal seismogenic processes in the Apennines determine activation of normal faults oriented parallel to the belt axis (Fig. 5b). One of the most recent and nice example of this fact is the sequence of earthquakes that struck, in September and October 1997, the Umbria-Marche Apennines (Central Italy). These earthquakes occurred on NW-oriented normal faults (Ekstrom *et al.,* 1998), such as done by previous earthquakes in adjacent regions (Fig. 5b) and coherently with the stress field inferred from our data. Other recent or possibly active faults, such as the N-S oriented left-lateral strike-slip faults mapped by Cello *et al.* (1997) do not appear to have a seismic expression, at least at this time.

Similarly, in the southern Apennines, where an extensional stress regime prevails (Fig. 5b), the most recent earthquake (Mw = 6.9 in 1980) revealed the presence of new NW-oriented active faults plunging towards the Adriatic Sea (Pantosti & Valensise, 1990) which had not been previously mapped.

The two aforesaid earthquakes — the 1980 one in the southern Apennines, and that of 1997 in the northern Apennines — differ mainly because, whereas the former ruptured a "new" fault, the latter probably used an "inverted" thrust fault. Hence, the relationship between active (seismic) faults and mapped faults is not yet clear for many regions of Italy. The knowledge of the present-day stress field is therefore important for assessing the seismic potential of known geologic structures.

The difficult recognition of active tectonic structures in the field can be due to different reasons:

1) active faults are not so evident because of low strain rates (few millimeters per year or less);

2) the stress field has recently changed at least in the southern Apennines as suggested by various Authors (Pantosti *et al.*, 1993; Westaway, 1993; Hippolyte *et al.*, 1994);

3) a combination of 1) and 2).

Furthermore, a reliable active stress map will serve as a basic tool to constrain and better understand the forces that are deforming the Italian region (Rebai *et al.*, 1992; Bassi & Sabadini, 1994). The integration of stress data with seismicity patterns, determined from instrumental monitoring and historical information, broaden our possibility to assess the seismic hazard in Italy. The regional consistency of stress orientations allows for the definition of broad-scale regional stress provinces and, even if we sample very different rock volumes and depth ranges, it indicates that in most places a uniform stress field exists throughout the upper brittle crust and within large stress provinces.

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