Journal of Structural Geology, Vol. 4, No. 4, pp. 385 to 393, 1982
Printed in Great Britain

0191-8141/82/040385-09 $03.00/0

Geometry of the neotectonic stress field in southern Italy: geological and seismological evidence

GIUSEPPE CELLO, IGNAZIO GUERRA, LUIGI TORTORICI, EUGENIO TURCO

Università della Calabria, Dipartimento di Scienze della Terra 87030 Castiglione Scalo, Cosenza, Italy

and

ROBERTO SCARPA

Osservatorio Vesuviano, Napoli, Italy

(*Received 1 February 1982; accepted in revised form 22 June 1982*)

Abstract—The neotectonic regime in southern Italy has been evaluated by making a comparison between all the available structural and seismological data. The area investigated can be subdivided into four distinct zones which are characterized by different stress regimes. In the Southern Apennines the tensile axis of the stress field is oriented approximately NE–SW while the maximum principal stress (σ_1) is subvertical. In Northern Calabria, the tensile axis is ESE–WNW and the σ_1 axis is almost vertical. In the Catanzaro trough both the tensile axis and the σ_1 axis are subhorizontal and act E–W and N–S, respectively. Finally, the Strait of Messina zone is characterized by a tensile axis oriented E–W and by σ_1 being subvertical.

INTRODUCTION

SOUTHERN Italy is one of the most seismically active areas in the Western Mediterranean. It is characterized by intense surface seismic activity and by the occurrence of intermediate and deep focus earthquakes located beneath the southern Tyrrhenian Sea (Gasparini *et al.* 1982) The reconstruction of the present-day stress regime in the area is, therefore, of great interest for defining seismogenetic structures, for obtaining information about processes occurring at the earthquake sources and for a general understanding of the dynamic evolution of the lithosphere (Mercier *et al.* 1979). It is well known that the evaluation of stress field characteristics can be achieved by different methods: *in situ* stress measurements, fault plane solutions of earthquakes and structural analysis.

In situ stress measurements, despite interpretative difficulties, are extremely useful for the definition of stress field geometry and, especially, for obtaining information about the effective values to be assigned to the three principal stress components ($\sigma_1 > \sigma_2 > \sigma_3$). Unfortunately, such measurements are difficult to extrapolate in space because they can be affected by very local factors which do not reflect the regional pattern of the stress field.

Focal mechanisms of earthquakes are of great use in those regions where geological structures are seismically active but, as with *in situ* stress measurements, seismological analysis provides information only on the present-day configuration of the stress field. For these reasons structural analysis, where applied in conjunction with the other methods, is a useful and powerful tool to extend the required information in space and time.

Because there are no presently available results on *in situ* stress measurements for southern Italy, we are concerned in this paper only with the geometrical characteristics of the stress field as derived from a comparison between structural data (collected in a few test areas) and seismological data relative to a set of fault plane solutions of crustal seismic events which have occurred since the beginning of this century.

STRUCTURAL SETTING

According to Scandone (1979) and Cello *et al.* (in press) Southern Italy comprises five main structural elements (Fig. 1).

The Apulian foreland, located to the east, is considered to be the African margin of the chain (Scandone 1979). It is made up of a thick carbonate sequence resting on a differentiated crystalline basement.

The Bradanic trough, which is characterized by Plio-Pleistocene sediments, is filled mainly by clays grading upwards to coarse-grained deposits.

The Apenninic chain, which is made up of several nappes belonging to different palaeogeographic domains, has been built up since Burdigalian time and its vergence (direction of tectonic transport) is towards the African foreland.

The Calabrian–Alpine chain consists of different tectonic units composed of ophiolites and their sedimentary cover (derived from Tethys) and of metamorphic rocks (derived from the deformation of the African palaeomargin). The chain overlaps the Apenninic nappes and was built up during the Upper Cretaceous–Palaeogene; its direction of vergence is towards Europe.

The Tyrrhenian Sea, located at the western end of the system, represents a recent extensional feature related to rifting processes which started about 12 Ma ago in connection with the upwelling of asthenospheric mantle (Scandone 1979).

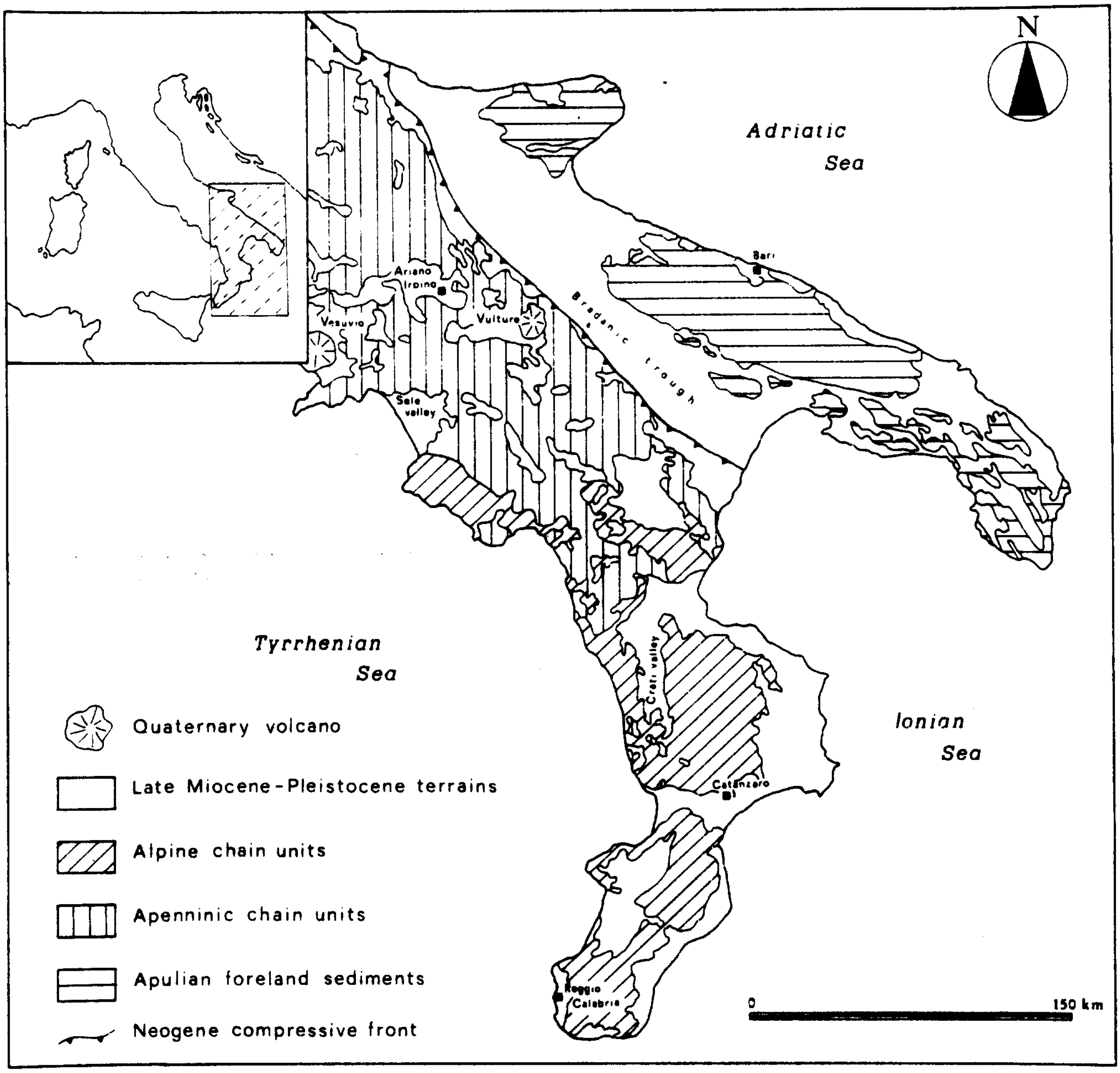

Fig. 1. Structural sketch map of southern Italy.

STRUCTURAL DATA

The structural data used for the present study were collected mainly from middle–late Pleistocene sediments and from middle–late Pliocene–early Pleistocene sequences in several intra-chain basins.

For the Southern Apennines we analysed brittle structures affecting middle Pliocene fine-grained sands in the Ariano–Irpino basin, pyroclastites of the Mount Vulture Volcano (0.5 Ma), Gunz–Mindel conglomerates exposed in the Lower Sele Valley and Mindel–Riss lacustrine sediments in the Mercure basin.

The structures observed in the Ariano–Irpino basin are mainly mesofaults, striking WNW–ESE, which show decimetric vertical displacements whereas the Mount Vulture pyroclastites are affected by two fault systems striking NNE–SSW and WNW–ESE, respectively. The NNE–SSW directed structures are the most abundant and are characterized by normal faults with a minor left-lateral component of motion (Table 1 and Figs. 2a & b).

Data collected in the Sele Valley show that the conglomerates are affected mainly by WNW–ESE and NE–SW trending fault planes characterized by vertical displacements ranging from a few centimetres to a few metres. Evidence of strike-slip motion with left-lateral shear occurs on some of the WNW–ESE oriented structures and right-lateral shear on some of the NE–SW faults. A third set of structures, which represents less than 10% of the total number of measurements taken in this area, is characterized by extension fractures striking ENE–WSW (Table 1 and Figs. 2c & d). Finally, in the lacustrine sediments of the Mercure basin there are only a few mesofaults which show decimetric displacements,

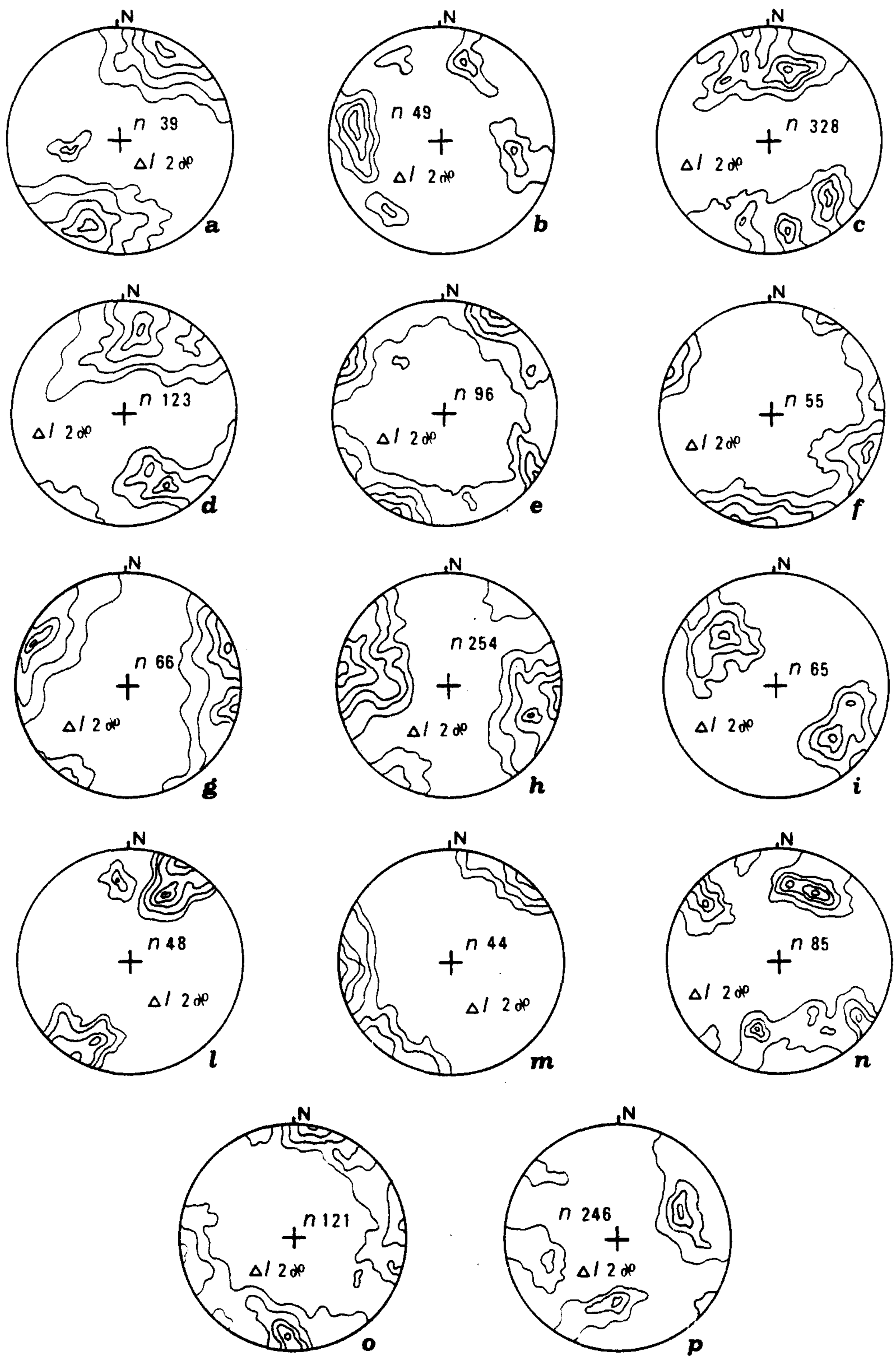

Fig. 2. Pole density diagrams (lower hemisphere Schmidt projection) of minor faults and joints. (a) Low Sele valley conglomerates. (b) Mt. Vulture pyroclastites. (c) Lacustrine deposits of the Mercure basin. (d) Marine terrace deposits of eastern Calabria. (e), (f) and (g) Sediments of the Catanzaro trough. (h) and (i) Coarse-grained deposits of the Reggio Calabria basin. (l) (m) and (n) Middle–upper Pleistocene terrace deposits of the Catanzaro trough. (o) Late Pliocene–late Pleistocene sediments of the Reggio Calabria basin. (p) Mesofaults and extension fractures from Bousquet *et al.* (1980). For further explanation see text. For each diagram the total number of measurements (n) and the density lines intervals (Δ*l*) are also given.

Table 1. Location data and solutions obtained from structural analysis

N	Nt	Lat	Lon	StA	PlA	StB	PlB	Ta	Pa	Tb	Pb	Tc	Pc
a	39	41.03	15.10	102	70NE	111	67SW	115	87	296	10	208	02
b	49	40.55	15.45	010	70E	110	64SW	330	30	158	55	062	05
c	328	40.32	14.58	050	45NW	110	60SW	068	58	270	32	178	05
d	123	40.35	15.10	060	50NW	100	70SW	076	48	272	40	172	10
e	96	39.58	16.00	030	85NW	115	88NE	071	02	310	88	160	00
f	55	39.55	16.06	025	80NW	108	85NE	068	08	300	85	152	05
g	66	39.48	16.30	015	82W	026	78SE	026	77	187	03	268	00
h	254	39.30	16.15	010	85E	034	74NW	210	50	020	55	110	20
i	65	39.32	16.54	048	60SE	050	75NW	160	82	050	00	318	10
l	48	38.55	16.45	109	70N	118	60SW	134	73	314	10	021	10
m	44	38.53	16.25	130	80SW	175	85E	332	16	160	70	061	03
n	85	38.40	16.02	038	72SE	115	65SW	089	05	180	62	348	26
o	121	38.00	15.42	102	80SW	175	90	318	05	160	87	045	02
p	246	38.10	15.42	008	75E	031	65NW	215	85	011	05	108	02

N, catalogue letter, for location see Fig. 6; Nt, number of measurements; Lat, latitude; Lon, longitude; StA, strike of the A plane; PlA, plunge of the A plane; StB, strike of the B plane; PlB, plunge of the B plane; Ta, trend of the σ_1 axis; Pa, plunge of the σ_1 axis; Tb, trend of the σ_2 axis; Pb, plunge of the σ_2 axis; Tc, trend of the σ_3 axis; Pc, plunge of the σ_3 axis.

while most of the observed structures are joints striking NE–SW and NW–SE (Table 1 and Figs. 2e & f).

For Northern Calabria, data were collected from late Pliocene–early Pleistocene sediments in the Crati basin and from marine terrace deposits ascribed to the late Pleistocene. The structures affecting these sediments are mostly normal mesofaults striking NNE–SSW (Table 1 and Figs. 2g & i). Supplementary information relative to this area was taken from Tortorici (1981) (Table 1 and Fig. 2h).

Other data were collected in the middle–upper Pleistocene terrace deposits of the Catanzaro trough. The structures observed consist of normal mesofaults and joints generally striking NW–SE (Table 1 and Figs. 2l–n).

In Southern Calabria we measured normal mesofaults affecting late Pliocene–late Pleistocene sediments in the Reggio Calabria basin (Table 1 and Fig. 2o). Data on 246 mesofaults and extension fractures, taken from Bousquet *et al.* (1980), were replotted (Table 1 and Fig. 2p).

A statistical analysis of the minor structures allowed us to define the complete geometry of the stress field

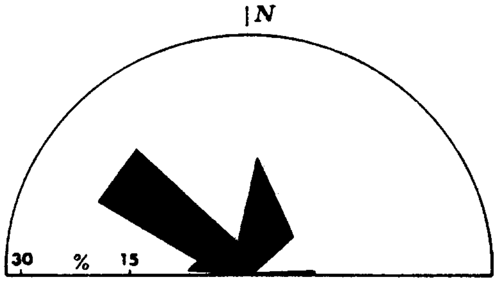

Fig. 3. Rose diagram showing the strikes of ground deformations generated by the main seismic event of the 23 November 1980 earthquake (modified from Carmignani *et al.* in press).

acting in each area. Relationships between tectonic discontinuity surfaces (joints and faults) and the state of stress responsible for generating them can be inferred on the basis of generalized rupture criteria of the Mohr–Coulomb type (Anderson 1951, Friedman 1964). For further discussion about methodological constraints see Kohlbeck & Scheidegger (1977) and Hancock & Barka (1981). The solutions obtained are listed in Table 1.

For the Southern Apennines, structural data are too scanty to be significant for the whole area; nevertheless the available information gave us the opportunity to evaluate the stress regime in the mesoseismic zone of the 23 November 1980 earthquake (Cello *et al.* in press). The area is subject to a general extension in a NNE–SSW direction, as derived from the analysis of 490 measurements collected from three stations located within the mesoseismic zone itself (Figs. 2b–d and Fig. 5). Supplementary information relative to ground deformations generated in connection with the main seismic event was taken from Carmignani *et al.* (in press). If one considers the N–S and NW–SE frequency maxima depicted in Fig. 3 as representing conjugate sets of shear fractures, then it follows that the orientation of the horizontal component of the σ_3 axis is approximately the same as inferred earlier.

More complete studies have already been carried out in Northern Calabria (Guerra *et al.* in press). The results of these studies provide evidence that the area investigated is mainly characterized by a WNW–ESE extension. A completely different pattern has been obtained for a narrow zone located within the Catanzaro trough. Here the σ_3 axis shows a significant variation from a N–S to ENE–WSW direction.

For Southern Calabria data relative to brittle deformation affecting the sediments of the Reggio

Table 2. Location data and fault plane solutions of crustal earthquakes of $4 < M < 7$ which have occurred in Southern Italy during this century

N	Date	Hh	Lat	Lon	H	*M*	StA	PlA	StB	PlB	Pt	Pp	Bt	Bp	Tt	Tp
1	8. 9.1905	01.43	38.25	16.00	10	7.0	045	77NW	137	79NE	090	02	351	65	181	17
2	28.12.1908	04.20	38.12	15.60	10	7.0	028	55NW	169	48NE	173	68	281	07	013	20
3	11. 5.1047	06.22	38.69	16.78	14	5.6	026	77NW	122	68NE	162	25	358	65	255	06
4	21. 8.1962	18.09	41.23	15.01	25	5.7	032	65SE	118	81NE	347	11	099	64	252	24
5	21. 8.1962	18.19	41.25	15.05	28	6.1	012	34NW	134	70NE	187	56	324	27	065	20
6	6. 5.1971	03.45	41.20	15.24	33	4.8	072	86NW	162	86NE	297	02	039	83	207	07
7	13. 4.1973	08.12	38.97	16.92	43	4.5	031	89SE	067	03NW	124	44	031	03	299	46
8	8. 8.1973	14.36	40.72	15.41	5	4.6	026	86SE	113	54NE	256	62	027	51	154	68
9	16. 1.1975	00.09	38.14	15.71	21	4.6	062	85SE	152	58NE	192	19	070	58	292	26
10	15. 4.1978	23.33	38.29	15.70	10	5.6	060	72NW	147	83SW	194	08	306	71	102	18
11	20. 2.1980	02.34	39.32	16.20	10	4.4	007	47W	062	58SE	026	59	220	31	127	07
12	20. 2.1980	02.40	39.33	16.19	10	4.3	030	48NW	042	43SE	057	83	215	07	306	03
13	9. 3.1980	12.00	39.99	15.91	10	4.3	022	61NW	068	39SE	066	64	216	24	312	11
14	14. 5.1980	01.40	40.36	15.77	15	4.2	120	61NE	130	30SW	197	74	302	05	034	16
15	32.11.1980	18.34	40.77	15.30	18	6.8	118	64NE	145	29SW	183	68	303	12	037	18

N, catalogue number, for location see Fig. 6. Hh, time; Lat, latitude; Lon, longitude; H, depth; *M*, magnitude; StA, strike of the A plane; PlA, plunge of the A plane; StB, strike of the B plane; PlB, plunge of the B plane; Pt, trend of the P axis; Pp, plunge of the P axis; Bt, trend of the B axis; Bp, plunge of the B axis; Tt, trend of the T axis; Tp, plunge of the T axis.

Calabria basin indicate that a more complicated pattern of σ_3 axes exists in the Strait of Messina area. Perhaps this could be explained by either the fact that the number of measurements taken in some of the stations was insufficient for obtaining a statistically significant solution, or that the method of analysis does not eliminate spurious deviations about the mean values. Alternatively, one must admit that it is possible to find consistent variations in the stress-field geometry within a very narrow zone. More recent data relative to middle Pleistocene terrains seem, however, to confirm a general E–W extension (unpublished data).

SEISMOLOGICAL DATA

Earthquakes of $M > 4$ which have occurred in Southern Italy in this century, are listed in Table 2 together with the nodal planes of their fault plane solutions. *P*-wave polarity distribution has been matched to a double-couple source model in order to evaluate the nodal planes. Incidence angles have been calculated according to the travel-time tables given by Herrin *et al.* (1968). The evidence has been discussed previously by Gasparini *et al.* (1982) but further information concerning the 8 September 1905 and 8 August 1973 earthquakes is used in the present work. Data and results are given in Fig. 4 and plotted in Fig. 5 on an equal-area, lower-hemisphere, projection. It is possible to evaluate the reliability of individual fault plane solutions from Fig. 4, and, as can be seen, there is a marked difference in the quality of the data as a result of the wide ranges in both time and magnitude. For some of the solutions, for example the one relative to the 1905 earthquake, the identification of the nodal planes largely remains uncertain. Nevertheless the solutions obtained show that, in the whole region, the predominant motion during the largest earthquakes is related to normal faulting. Secondary strike–slip motion is present for smaller earthquakes and is distributed along the boundaries of the structural segments into which the Calabrian arc and the Southern Apennines are divided. This pattern is compatible with the fault plane solutions obtained and with the character of the deep and intermediate earthquakes of the Southern Tyrrhenian Sea. However, the most outstanding feature made evident by seismological analysis, is represented by a significant variation of the dip and azimuth of the tensile (T) axis between the Southern Apennines and the Calabria–Peloritani arc. In Northern Calabria two fault plane solutions relative to small earthquakes occurring on 20 February 1980 (M_l = 4.4 and 4.3) indicate tensile stresses oriented NNW–SSE. An $M_l = 5.6$ crustal earthquake which occurred in the Gulf of Squillace area on 11 May 1947 indicates strike–slip motion with the T axis oriented E–W. Normal faulting with the same orientation accompanied the Strait of Messina earthquake which occurred on 18 December 1908 (M_s = 7.0).

In the Southern Apennines a variety of fault plane solutions exist, indicating the predominance of normal faults striking in the same direction as the mountain range. Strike–slip motion is present in the Gargano region and along the lateral segments of the chain. In particular, this type of motion is made evident by fault plane solutions relative to a structure connecting the Gargano region to Vesuvius. It is also important to note

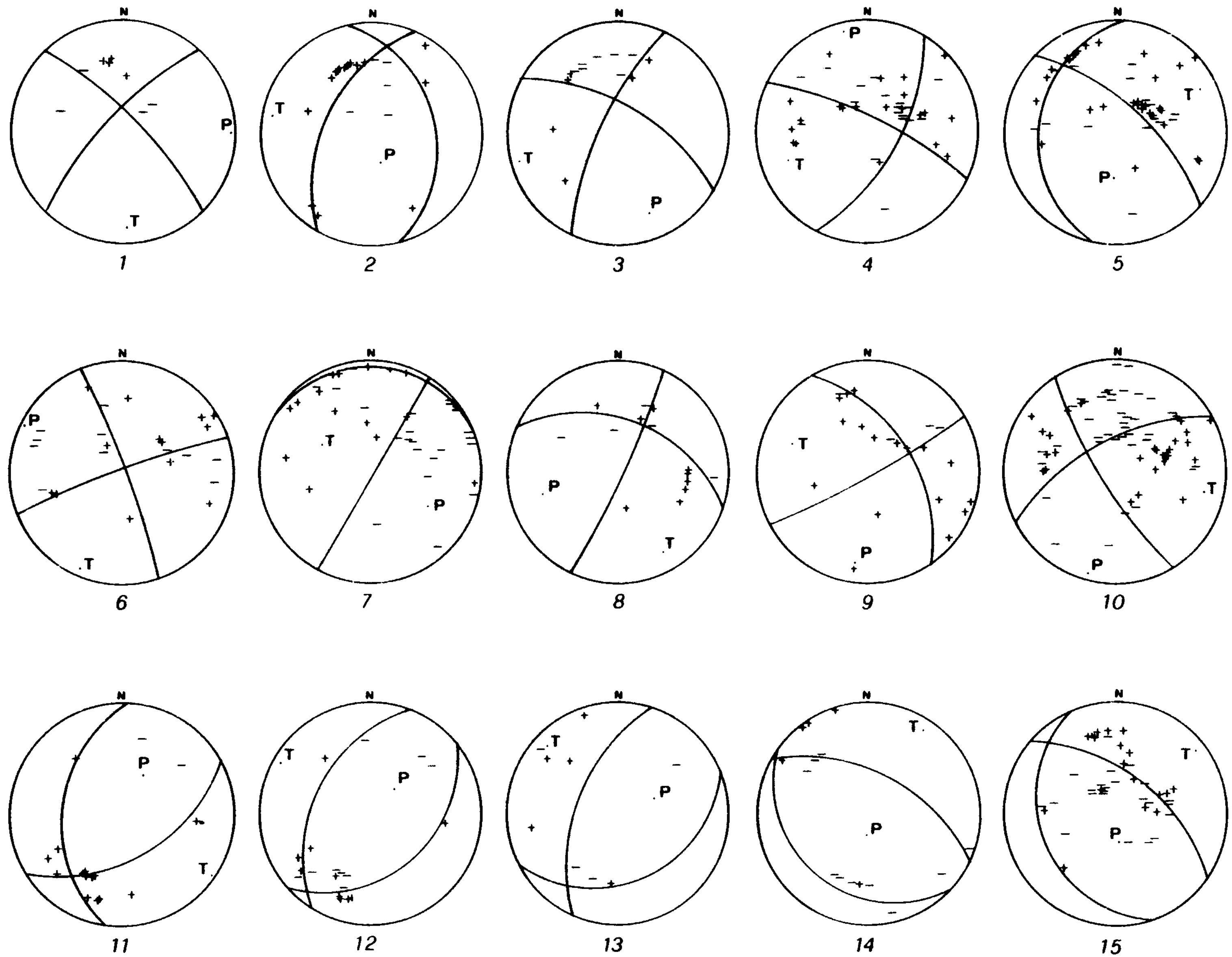

Fig. 4. *P*-wave polarity distribution and fault plane solutions for the earthquakes listed in Table 2. +, compression; –, dilatation. The orientations of the P and T axes are also shown.

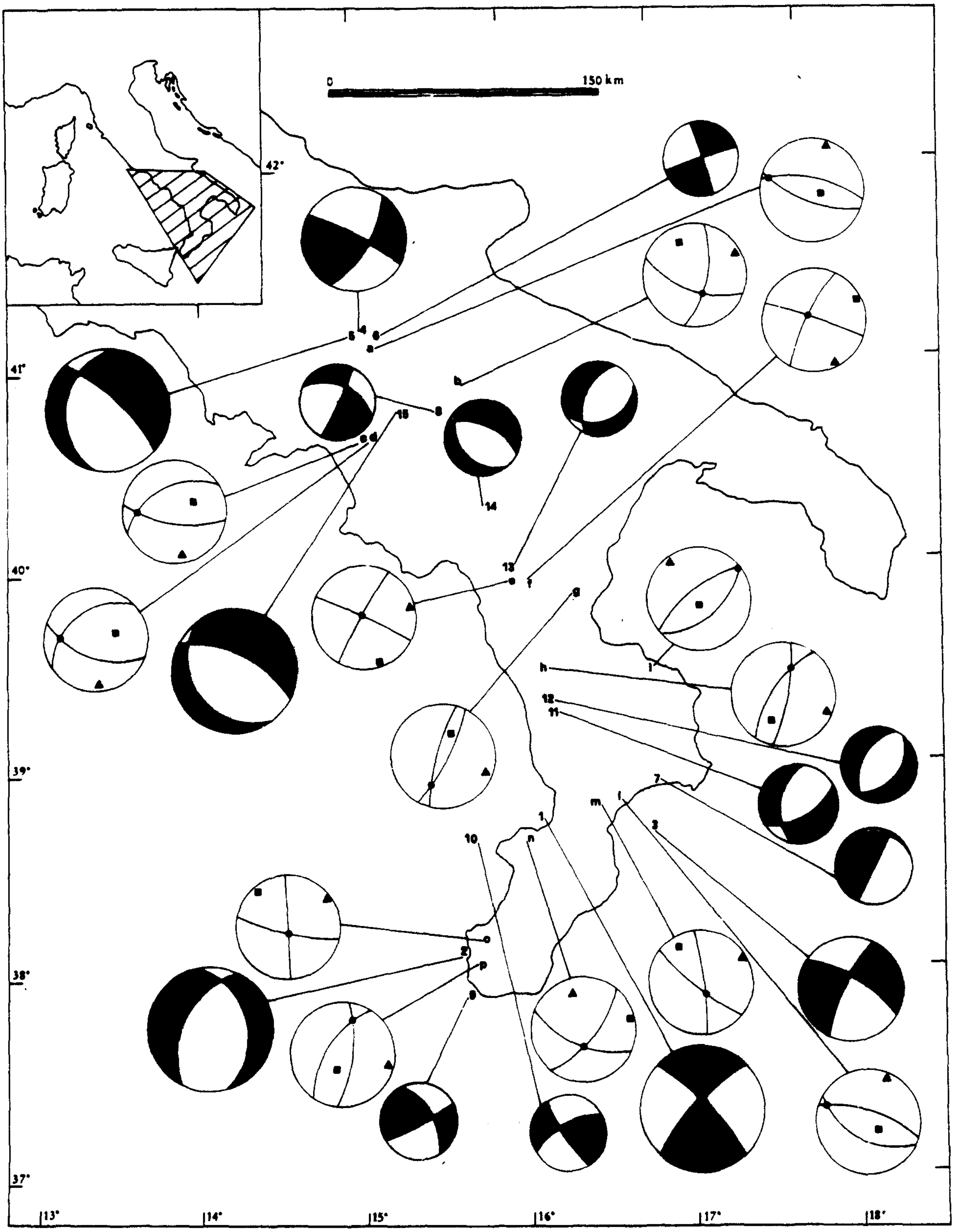

Fig. 5. Stress field geometry in southern Italy as derived from seismological and structural data. Fault plane solutions relative to crustal earthquakes with $4 < M < 7$ are indicated using the same numbers given in Table 2. Structural solutions are indicated with letters (see Table 1). For the latter solutions σ_1 (■), σ_2 (●) and σ_3 (▲) axes are also given.

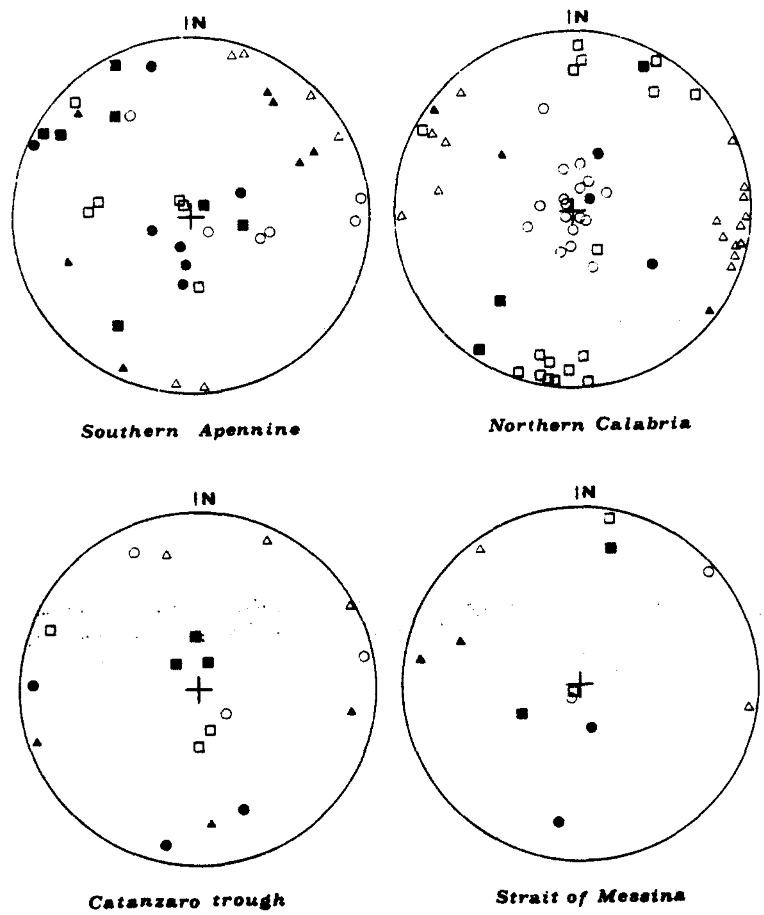

Fig. 6. Schmidt projection (lower hemisphere) of principal stress directions. Circles represent σ_1 axes, squares σ_2 axes and triangles σ_3 axes; open symbols refer to solutions derived from structural analysis and closed symbols refer to fault plane solutions.

that this structure limits the northwestern side of the rupture zone of the 23 November 1980 earthquake (Gruppo di Lavoro Sismometria in press).

CONCLUDING REMARKS

On the basis of the structural and seismological data relevant to the area under examination, we conclude that it is possible to distinguish four distinct zones which are characterized by different stress field patterns; the Southern Apennines, Northern Calabria, the Catanzaro trough and the Strait of Messina.

All the available information relevant to the geometrical characteristics of the stress field acting in each zone is summarized in Fig. 6. For Northern Calabria, data pertinent to neotectonic terrains where the last phase of deformation has been recognized (Tortorici 1981) have also been plotted.

A comparison between the sets of seismological and structural data relevant to the Plio-Pleistocene terrains can be made by reference to Fig. 5. The general agreement between the solutions obtained by using the two different techniques confirms the occurrence of a complicated pattern of stress regimes in Southern Italy. In particular, in the Southern Apennines, the orientation of the three principal stress axes is such as to generate dip–slip and/or left-lateral strike–slip motion on NW–SE oriented fault planes, and right-lateral strike–slip motion on NE–SW oriented falt planes.

For Northern Calabria the stress field geometry indicates that the neotectonic regime of the area generates essentially normal faulting on N–S and NNE–SSW directed structures. However, for the Catanzaro trough zone it seems that there is a rotation of the stress field and right-lateral strike–slip motion on fault planes roughly oriented WNW–ESE can be inferred. Finally, for the Strait of Messina zone the neotectonic regime is such as to cause dip-slip motion on NE–SW oriented fault planes and left-lateral strike–slip motion on E–W faults.

These significant variations need to be explained by a regional geodynamic model which must be capable of taking into account the occurrence of a differentiated neotectonic stress regime in Southern Italy. For this reason it might be helpful to consider the area investigated as part of a larger kinematic system (the Mediterranean orogenic belt), which is affected by second-order processes such as the recent rifting of the Tyrrhenian Sea, which, perhaps, could explain the lateral segmentation of the Southern Apennines and the strong curvature of the Calabria–Peloritani arc. In order to test this working hypothesis a major effort aimed at acquiring and analysing more data in the fields of structural geology, rock mechanics and seismology is needed. This, we hope, will allow us to work out a semiquantitative model for such a complicated system and permit us to evaluate those dynamic effects which it is necessary to understand in order to prepare a seismotectonic map of Southern Italy.

REFERENCES

Anderson, E. M. 1951. *The Dynamics of Faulting* (2nd Ed) Oliver & Boyd, Edinburgh.

Bousquet, J. C. Carveni, P., Lanzafame, G., Philip, H. & Tortorici, L. 1980. La distension pléistocene sur le bord oriental du détroit de Messine: analogie entre les résultats microtectoniques et le mécanisme au foyer du séisme de 1908. *Bull. Soc. géol. Fr.* **22**, 327–336.

Carmignani, L., Cello, G., Cerrina Seroni, A., Funiciello, R., Kalin, O., Meccheri, M., Patacca, E., Pertusati, P., Plesi, G., Salvini, F., Scandone, P., Tortorici, L., & Turco, E. in press. Analisi del campo di fratturazione superficiale del terremoto campano-lucano del 23–11–1980. Atti del Convegno P. F. Geodinamica, Udine 12–14 Maggio 1981. *Rc. Soc. geol. ital.*

Cello, G., Tortorici, L. & Turco, E. in press. Analisi mesostrutturale dei dépositi conglomeratici della bassa valle del F. Sele (Salerno). Atti del Convegno "Il terremoto del 23–11–1980", Napoli 2–3 Aprile 1981. *Rc. Soc. geol. ital.*

Cello, G., Tortorici, L., Turco, E. & Guerra, I. 1981. Profili profondi in Calabria settentrionale. *Boll. Soc. geol. ital.* **100**, 423–431.

Gasparini, G., Iannaccone, G., Scandone, P. & Scarpa, R. 1982. Seismotectonics of the Calabria Arc. *Tectonophysics* **84**, 267–286.

Gruppo di lavoro Sismometria, in press. Il terremoto campano-lucano del 23-11-1980: elaborazione preliminaire dei dati sismometrici. Atti del Convegno P. F. Geodinamica, Udine 12–14 Maggio 1981. *Rc. Soc. geol. ital.*

Guerra, I., Scarpa, R., Tortorici, L. & Turco, E., in press. Geometria del campo tensionale agente in Calabria settentrionale: confronti tra metodologie strutturali e sismologiche. Atti del Convegno "Il terremoto del 23-11-1980", Napoli 2–3 Aprile 1981. *Rc. Soc. geol. ital.*

Hancock, P. L. & Barka, A. A. 1981. Opposed shear senses inferred from neotectonic mesofracture systems in the North Anatolian fault zone. *J. Struct. Geol.* **3**, 383–392.

Herrin, E., Arnold, E. P., Bolt, B. A., Clawson, G. G., Engdahl, E R., Freedman, H. W., Gordon, D. W., Hales, A. L. Lobdell, J. L., Nuttli, O., Romney, G., Taggart, J. & Tucker, W. 1968. Seismological tables for P phases. *Bull. seism. Soc. Am.* **58**, 1193–1352.

Kohlbeck, F. & Scheidegger, A. E. 1977. On the theory of the evaluation of joint orientation measurements. *Rock Mech.* **9**, 9–25.

Mercier, J. L., Delibassis, N., Gauthier, A., Jarrige, J. J., Lemeille, F., Philip, H., Sebrier, M. & Sorel, D. 1979. La néotectonique de l'Arc Egéen. *Revue Geogr. phys. Geol. dyn.* **21**, 67–92.

Scandone, P. 1979. Origin of the Tyrrhenian Sea. *Boll. Soc. geol. ital.* **98**, 27–34.

Tortorici, L. 1981. Analisi delle deformazioni fragili dei sedimenti postorogeni della Calabria settentrionale. *Boll. Soc. geol. ital.* **100**, 291–308.