BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXVI, N. 141-144 - MARCH-DECEMBER 1994

A. MORETTI [1, 2], M. F. CURRÀ [1] and I. GUERRA [1]

SHALLOW SEISMIC ACTIVITY IN THE SOUTHEASTERN TYRRHENIAN SEA AND ALONG THE CALABRIA-LUCANIA BORDER, SOUTHERN ITALY

Abstract. Observation of shallow seismicity in the southern Tyrrhenian Sea is hindered both by its low energy and by geographical features that impose severe constraints on the distribution of land seismic stations. However seismic phenomena are of great importance for defining the present-day structural framework and stress field and for reconstructing the time evolution of such an interesting geological region. Therefore earthquakes even of low magnitude must be used to extract all possible information. On August 28, 1992, a seismic sequence started offshore Policastro Bay, in the area of the submarine volcanoes Enotrio and Palinuro, the main shock having local magnitude 3.8. It lasted until mid-October. The hypocentre locations were obtainable for the main shock and some tens of aftershocks. For the main shock the fault plane solution was also calculated. The results have stimulated analysis of seismic activity in the adjacent region on the Calabria-Lucania border, which has been characterized by moderate seismicity in historical times and by minor earthquakes in the most recent years. Both the macroseismic and instrumental data available are compatible with the hypothesis of a unique major seismogenic element being responsible for the seismic activity on land as well as offshore.

INTRODUCTION

The intermediate and deep seismicity of the southern Tyrrhenian Sea is generally considered a key to the reconstruction of geological evolution in that and surrounding areas, and is the object of a rich scientific literature. Conversely the shallow seismicity has been studied as yet only in a few zones of particular geological and structural interest (Aeolian Islands, Strait of Messina), or where it has caused significant macroseismic effects (Strait of Messina, Gulf of Patti).

However such scarce attention by geoscientists, is only apparent. In fact, study of the active shallow structures is crucial for a better understanding of the present-dat dynamics. On the other hand, the scarcity of scientific works on this particular subject is easily explained by the lack of instrumental observations for analyses based on a well-founded experimental basis. In fact the quality of seismographic data will rise to fully satisfactory levels only with difficulty due to the low energy of the seismic events and the particular configuration of the region.

The information collected in very recent years by the Calabria University seismic network (Fig. 1) displays a fairly abundant concentration of shallow foci 50-60 km offshore the Italian peninsula towards the center of the Tyrrhenian Basin (Fig. 2). Moreover, using Ocean Bottom Seismographs, Soloviev et al. (1990) observed microseismic activity in the area of the Palinuro submarine volcano not detected by seismic stations on land. Therefore one can attribute the lack of seismicity in the central part of the basin to the distance from seismic stations.

Manuscript received April 23, 1993; accepted April 4, 1994.

[1] Università della Calabria, Dipartimento di Scienze della Terra, 87036 Arcavacata (CS), Italy.

[2] Gruppo Nazionale Difesa dai Terremoti, via Nizza 128, 00185 Roma, Italy.

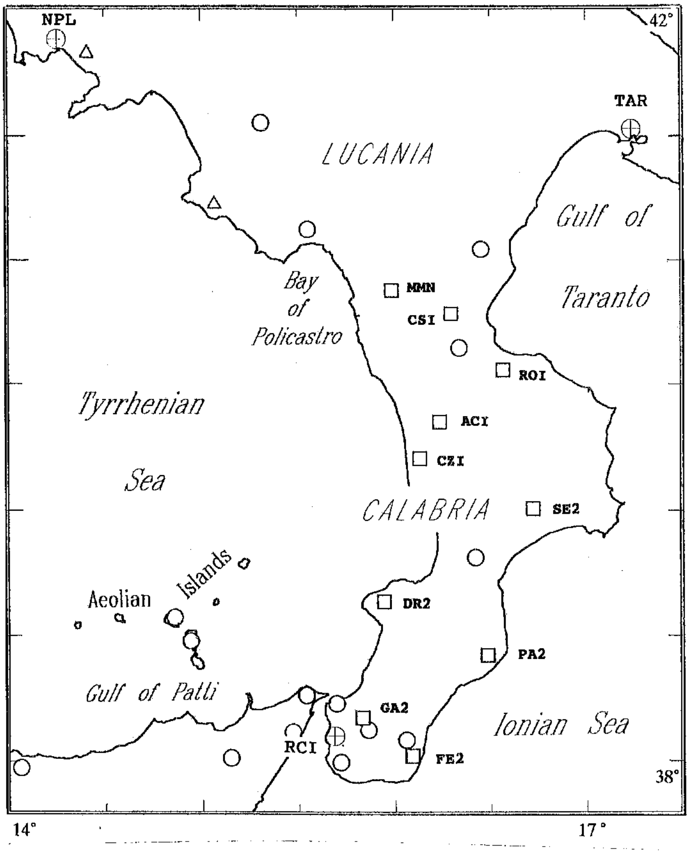


Fig. 1 — Seismic stations in southern Italy operated by the Italian National Institute of Geophysics (circles) and by Calabria University (squares). Further stations that furnished data used in this work are also reported (triangles). The locations of the three stations opened before 1978 are indicated by crosses inside circles.

In such a situation any experimental data has to be utilized to improve knowledge on the geodynamics of the area, carefully taking into account its reliability.

The study of the microseismic sequence which began on August 28, 1992, off the Bay of Policastro, offers the starting point for significant analyses. Its epicentral area is marked by the presence of the submarine volcanoes Enotrio and Palinuro (Fig. 3). According to Finetti and Del Ben (1986), the dominant geological structure is the transcurrent left-lateral Palinuro-Cetraro fault, striking roughly E-W and bounding southwards the Apennine continental margin. Only poor information is available for the area bordering the coast. Finetti and Del Ben (1986) hypothesize an ESE-WNW strike-slip fault; but Boccaletti et al. (1984) report normal faults bounding the Policastro Basin and trending NE-SW. Analysis of seismic activity might provide elements for solving these ambiguities and for putting additional constraints on the dynamics of this area.

THE AUGUST 1992 MICROSEISMIC SEQUENCE

A microseismic sequence started on August 28, 1992, at 13.05 GMT, with an earthquake of local magnitude 3.8 which was felt in Cosenza, about 90 km from the epicentre. It was recorded by several stations of the Italian National Seismic Network (Istituto Nazionale di Geofisica, Rome) and by the Seismic Network of Calabria University.

This array (Fig. 1) is made up of eight observation points equipped with vertical seismometers

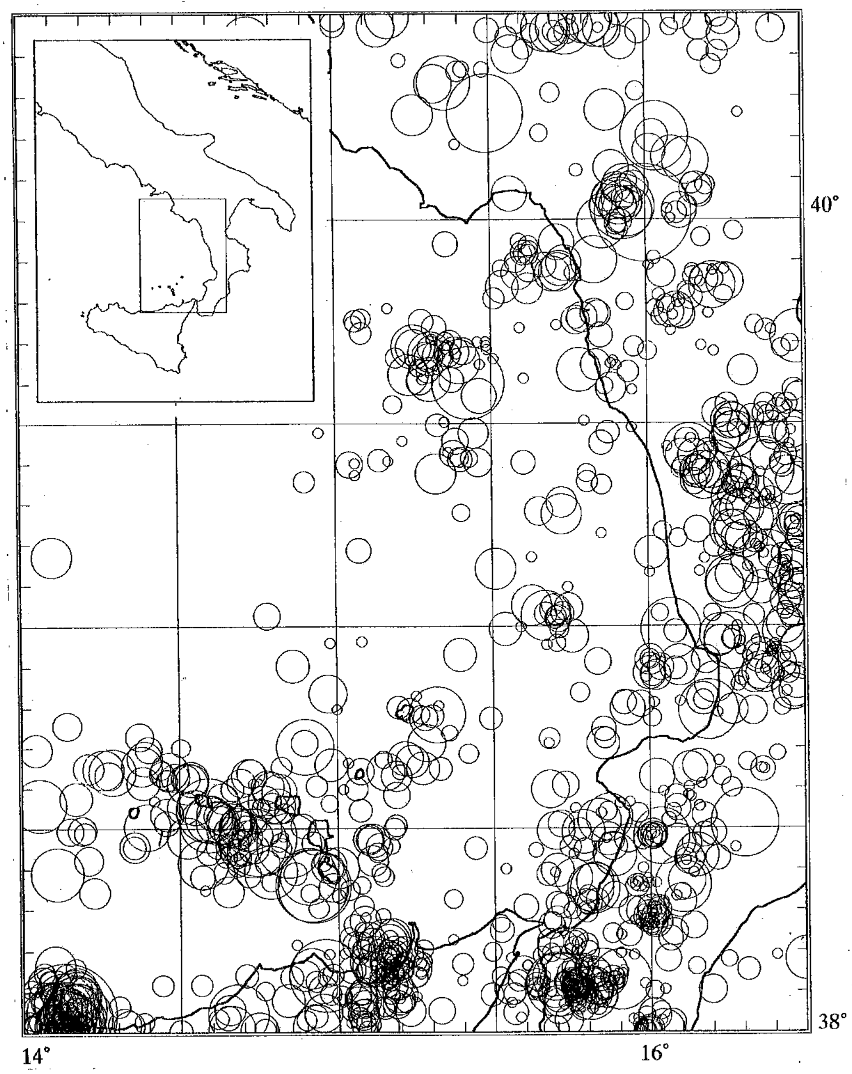


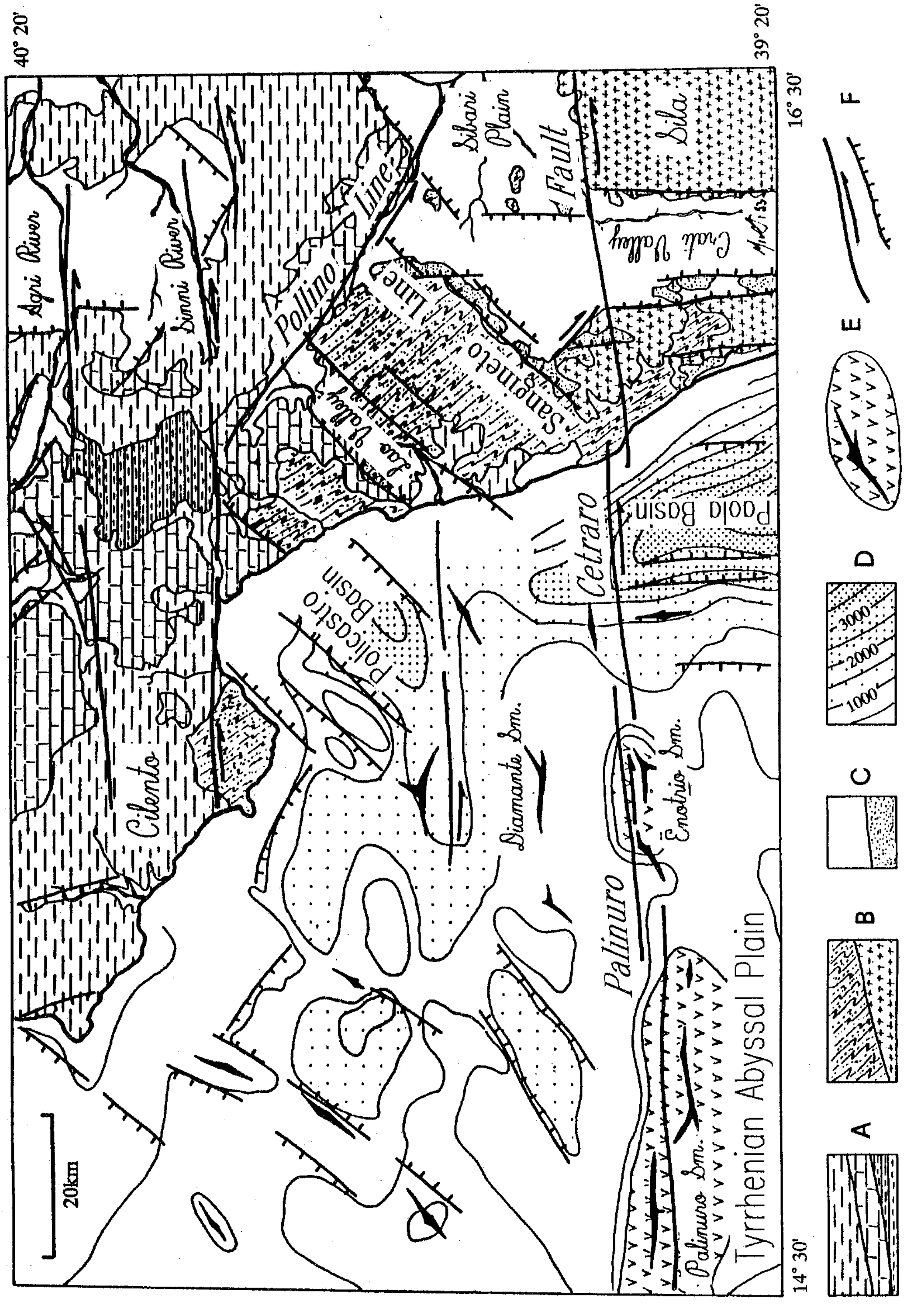
Fig. 2 — Surface distribution of shallow earthquakes (h < 50 km) from 1986 to 1992 according to arrival times at the stations of the Calabria University seismic network and the Italian National Seismic Network. Size of symbols depends on magnitude, ranging from 1 up to 4.8.

and linked by radio to the station ACI, where the recording system is installed. Here the incoming signals are contemporaneously monitored on paper and recorded on FM analogic magnetic tape. In the summer of 1992, moreover, a home-made digital recording system was being tested; with this all the analogic traces are sampled and can be displayed contemporaneously for time picking; therefore numeric records are also available for the seismic activity of that period.

In the summer 1992 a Lennartz MARS88 3-components digital seismograph was operating at MMN besides the usual local apparatus that has only a paper recorder. The time signal is generated by a quartz-clock controlled by DCF radio-signals.

The recording systems described above allow very accurate readings of the arrival times; the uncertainty in the hypocentral coordinates depends only on the structural model and on the geometry of the network.

The epicentre of the main shock of August 28 was located 39.56°N, 15.51°E, and the most probable hypocentral depth is 13 km from the computer program LME92 (Guerra et


40° 20'
39° 20'
14° 30'
16° 30'
20km
Agri River
Sinni River
Pollino Line
Sibari Plain
Fault
Sila
Crati Valley
Lao Valley
Sangineto Line
Cilento
Policastro Basin
Cetraro
Paola Basin
Diamante Sm.
Enotrio Sm.
Palinuro
Palinuro Sm.
Tyrrhenian Abyssal Plain
1000
2000
3000
A
B
C
D
E
F

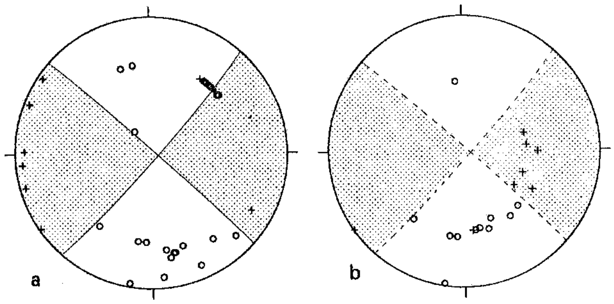


Fig. 4 — a) Fault plane solution for the main shock of August 28, 1992. Equal area projection, lower focal hemisphere. b) Plot on the same fault plane solution of the polarities at the stations nearest to the epicentre, according to the take-off angles coming from the LME92 location program. Crosses and circles represent compressions and dilatations respectively.

al., 1989; 1990). This code uses specific two-dimensional models with dipping plane interfaces for tracing the paths from the hypocentre to each seismic station; therefore it discards arrival times at distances greater than a given threshold. It is particularly suitable for areas exhibiting strong lateral variations in the geological structure.

Data used for locating the hypocentre were the readings at the Calabria University stations and those published by the Istituto Nazionale di Geofisica.

Thirty-five first motion polarities were available for determining the fault plane solution, including data from the Earthquake Data Report by USGS/NEIC. In this case, the incidence angle at the focus is computed from the travel times according to Herrin et al. (1968), and the search for the nodal planes is done using the Wickens and Hodgson method (1967). The focal solution best fitting the data (Fig. 4a) identifies three incorrect polarities and corresponds to a strike slip displacement along a vertical fault plane trending NW-SE or NE-SW. Its stability was tested by repeating the calculation with several different values for the focal depth; in the depth range from 5 up to 30 km all the solutions obtained are equivalent and characterized by similar values of the parameter *SCORE* (Wickens and Hodgson, 1967), which indicates their quality.

It might appear more reasonable to attribute the values resulting from the location algorithm to the take-off angles from the source; this however reduces the data utilizable to those from the nearest stations, which are concentrated in ranges of both azimuth and distance too narrow to allow for a reliable fault plane solution. These data however are coherent with the solution found using Herrin's tables (Fig. 4b).

The main shock of August 28 was preceded by a few foreshocks and followed by about fifty aftershocks lasting until mid-October. In the Table the catalogue of the earthquakes located by use of at least 9 data is reported. Their magnitude, ranging from 1.5 up to 3.8, was calculated from the duration of the seismograms. Source locations of the aftershocks were generally poor, and the epicentre distribution was accordingly scattered, as can be seen in Fig. 5.

Examining this figure, the 1992 activity can be attributed to two different clusters, whose populations grew contemporaneously. Due to the difficulties of the location procedure for that area and the uncertainties in the epicentral coordinates, a confirmation of the validity of this observation was sought.

Fig. 3 — Structural sketch-map.
A - South Apennines Units. Bottom to top: Lagonegro metamorphic Units, platform Units, external Units and Cenozoic terrigenous cover.
B - Calabride Units. Bottom to top: crystalline Units (granofels, amphibolites and gneiss), sedimentary metamorphic Units.
C - Post-orogenic Units. Bottom to top: Upper Tortonian-Messinian deposits, Pliocene-Quaternary deposits.
D - Thickness of the Pliocene-Quaternary deposits in marine areas.
E - Submarine volcanics and strike of main submarine ridges (black).
F - Dip-slip and strike-slip fault systems.

Table - Location parameters of the events of the 1992 seismic sequence.

No	Date	Origin time	Lat. (°N)	Long. (°E)	Depth (km)	m_d	Errors (km)		n. of data	Gap (°)	rms (sec)
							ΔN	ΔE			
1	920828	447 51.2	39.414	15.397	28	2.4	2.4	5.3	13	191	0.85
2	920828	512 11.1	39.428	15.361	21	2.0	1.8	3.4	9	259	0.39
3	920828	521 24.9	39.455	15.384	8	2.7	0.8	1.5	22	186	0.46
4	920828	1130 49.0	39.403	15.457	1	2.2	2.2	4.7	10	212	0.72
5	920828	13 5 39.9	39.600	15.427	13	3.8	1.1	1.7	47	150	0.56
6	920828	2333 36.1	39.429	15.435	43	2.2	1.7	3.9	15	201	0.63
7	920829	2026 22.0	39.547	15.186	30	2.3	2.4	4.0	10	218	0.63
8	920829	21 0 3.0	39.668	15.332	30	2.3	1.5	3.2	12	203	0.45
9	928030	1937 20.1	39.703	15.354	1	2.4	0.9	1.9	16	191	0.52
10	920902	454 51.0	39.686	15.307	5	2.7	1.3	2.7	20	195	0.76
11	920902	2226 41.9	39.679	15.411	25	2.1	2.3	4.2	14	196	0.80
12	920902	2342 4.4	39.669	15.291	2	2.6	1.1	2.2	19	196	0.63
13	920904	433 2.9	39.612	15.604	8	1.7	1.9	3.2	15	173	0.73
14	920905	1039 33.2	39.476	15.443	1	2.7	2.5	3.3	15	146	0.99
15	920906	818 53.2	39.671	15.363	27	2.5	1.4	2.0	16	221	0.43
16	920906	1456 49.1	39.692	15.486	13	1.8	2.8	4.1	10	189	0.92
17	920906	1712 10.1	39.496	15.327	3	2.7	1.6	3.0	17	156	0.77
18	920908	113 14.2	39.408	15.141	1	2.8	1.9	3.1	18	170	0.96
19	920908	1229 9.8	39.659	15.509	38	1.8	2.5	5.0	10	188	0.68
20	920912	727 30.6	39.672	15.389	35	1.9	4.3	6.5	9	228	0.83
21	920912	1310 58.6	39.701	15.484	16	2.1	1.7	3.1	12	205	0.48
22	920917	212 13.4	39.687	15.439	53	2.3	3.7	7.0	12	193	0.91
23	920925	2359 56.1	39.371	15.063	0	2.2	1.9	4.6	13	220	0.64
24	920925	1327 24.8	39.693	15.361	35	2.3	1.0	2.0	12	200	0.30
25	920926	23 0 1.7	39.634	15.330	31	1.5	5.7	10.3	10	235	1.00
26	920930	434 37.5	39.742	15.711	12	1.7	5.3	8.5	10	238	0.77
27	921001	547 7.4	39.656	15.245	31	1.5	2.7	5.7	9	211	0.76
28	921001	847 34.1	39.673	15.305	13	3.3	1.0	2.3	24	184	0.47
29	921004	1838 15.8	39.400	15.064	1	2.0	2.7	5.6	9	231	0.69
30	921004	2336 43.7	39.707	15.311	2	1.9	1.9	3.0	12	204	0.72
31	921008	2333 24.7	39.648	15.349	2	3.2	1.2	1.7	35	157	0.72

In effect seismic events belonging to the separate groups were found to be characterized by the first arrival time at the stations CZI and CSI respectively, by systematic delays among the arrival-times in two pairs of stations showing sharp onsets on the computer screen (Fig. 6); and by the differences in the shape of the seismograms recorded both by the permanent network and by the MARS88 seismograph at MMN.

PAST SEISMIC ACTIVITY

As already stated, the main shock was felt in Cosenza, some km 90 from the epicentre, the local intensity being estimated as the third degree on the MCS Scale. It was impossible to gather macroseismic information at intermediate distances, but the hypothesis that the shock was felt along the coast is reliable. In view of the seismic hazard assessment for the region, this makes it worth verifying whether or not geological submarine structures, activated in 1992, had already exhibited activity in the past. Indeed, on March 21, 1982, an earthquake caused permanent macroseismic effects in the settlements along the Tyrrhenian coast of northern Calabria. It was located at sea on the basis of both macroseismic and analytical data (Istituto Nazionale di Geofisica, 1982).

Macroseimic information on seismic activity in pre-instrumental times is found in the Catalogue of Italian Earthquakes edited by Postpischl (1985), the source of data utilized to draw Fig. 7, which represents the epicentres of earthquakes from 1000 to 1900. It can be noted that in the examined area seismic intensity in past centuries did not attain high values.

From Fig. 7 it is seen that no elements exist for locating any macroseismic epicentres at sea. However Branno et al. (1985) recently found new information on the earthquake of January 2, 1831 (I_0=VIII according to Postpischl, 1985), which was located by Baratta (1901) on

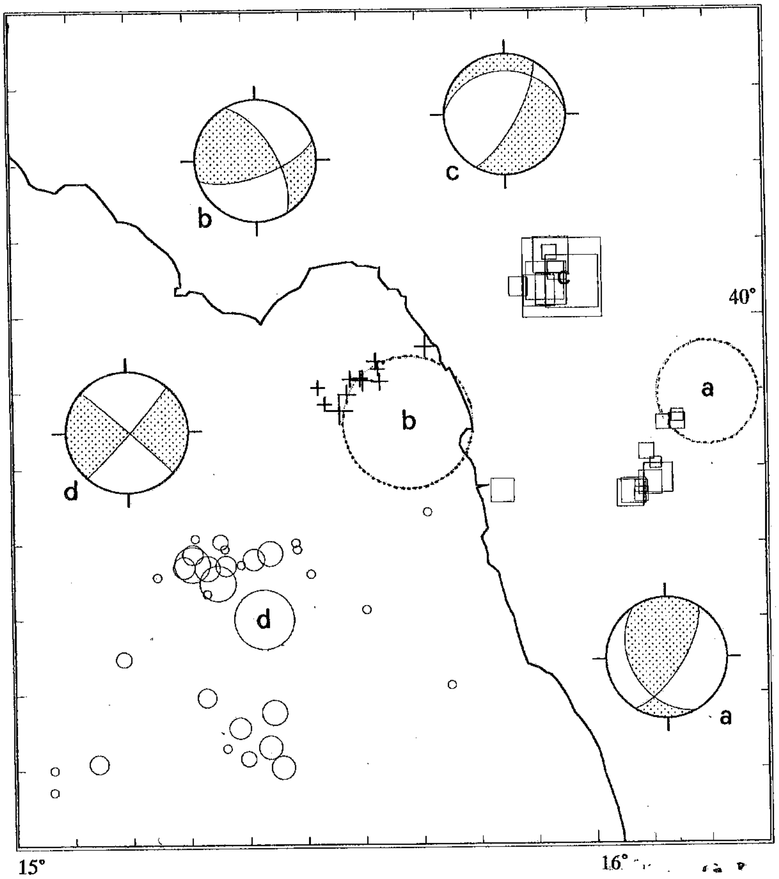


Fig. 5 — Fault plane solutions of earthquakes described in the text, and epicentres of different seismic sequences. Squares: January 8 and January 28, 1988; crosses: April 7, 1989; circles: August 28, 1992. Dotted circles indicate the earthquakes of March 9, 1980 (a) and March 21, 1982 (b). Size of symbols indicates magnitudes.

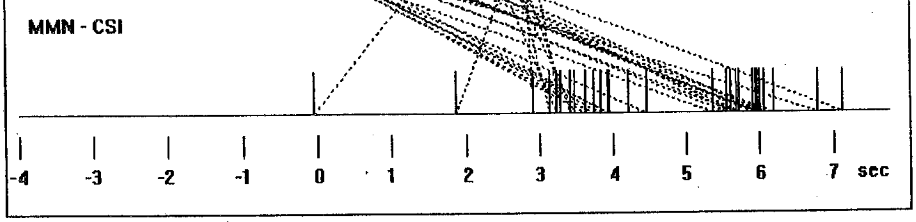


Fig. 6 — Comparison among arrival-time delays at the pairs of stations CSI-CZI (above) and MMN-CSI (below). Dotted lines join values for the same seismic events.

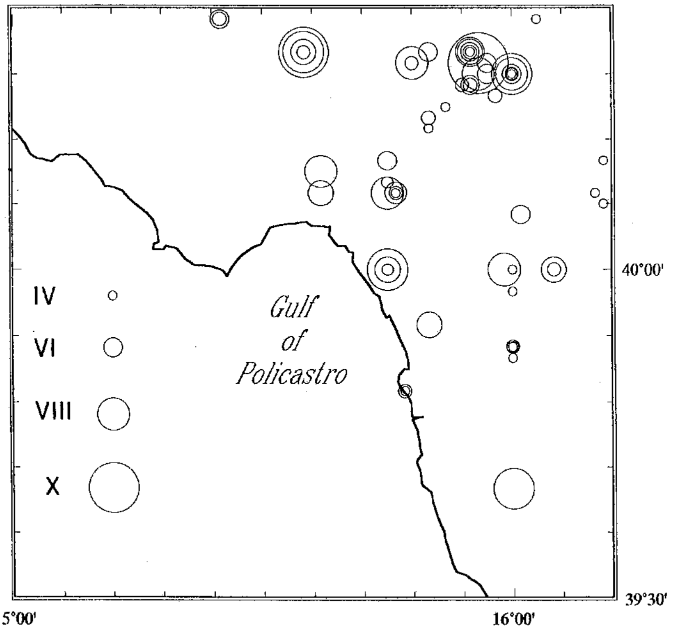


Fig. 7 — Epicentres of earthquakes from 1000 to 1900 a.D. (after Postpischl, 1985).

land, between Lagonegro and Lauria: after this earthquake, the chief of the district of Lagonegro reported to the Neapolitan central government that "... the violence of the phenomenon was most evident in the western villages of the district and, decreasing gradually, became barely perceptible fifty miles from the sea ...". Taking into account that communications from the minor settlements were at that time very difficult, and evaluating the soundness of the data available from Baratta (1901), the source of this seismic event at least might be located off the Tyrrhenian coast.

In the years from 1901 to 1980, the Catalogue of Italian Earthquakes (Postpischl, 1985) does not report for this area any seismic events with significant macroseismic intensity and, consequently, reliable epicentral location. On the other hand, seismic networks in southern Italy have developed in such a way that analytical locations of epicentres up to the early eighties are most likely less reliable than the macroseismic ones: until 1978 the nearest seismic stations were operating at NPL, TAR and RCI (Fig. 1), the last two being equipped with mechanical seismographs (TAR was closed in 1969).

The best presentation of shallow instrumental seismicity in the southeastern Tyrrhenian Sea and peninsular Calabria is therefore shown in Fig. 2, over a time span of only about ten years (1981-1992). In this case also hypocentral coordinates were calculated with program LME92, using data from Calabria University and the National Institute of Geophysics seismic stations. Only epicentres located with at least seven arrival times, and rms less than 1.5 sec are shown. At the scale of the figure, the effect of the array geometry on the space distribution of epicentres is meaningless.

In Fig. 2 two epicentre alignments trending NE-SW are evident in the area affected by seismic activity in 1992. These alignments are even clearer in Fig. 5, where the epicenters of 1992 are plotted together with three dense microseismic sequences recorded on January 8, 1988, January 28, 1988, and April 7, 1989. Their main shocks, with magnitudes of 4.1, 3.0 and 3.0, are the strongest events recorded in the respective epicentral areas since 1980. In this time span, only the above-mentioned earthquake of March 21, 1982, had greater magnitude ($m_l = 5.0$), but existing instrumental data are not sufficient to locate any of its approximately 120 aftershocks recorded at MMN, in most cases the only station where they

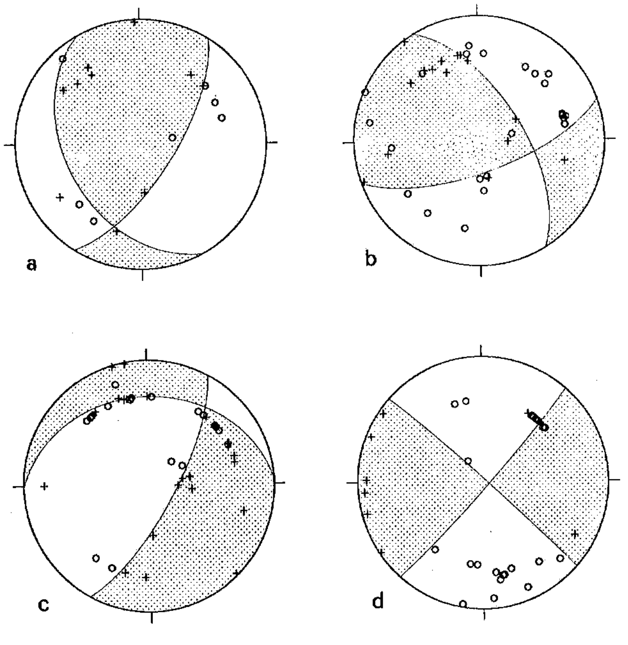


Fig. 8 — Fault plane solutions for earthquakes on the Calabria-Lucania border and in the adjacent sector of the Tyrrhenian Sea. Symbols as in Fig. 4. a) 1980 March 9, m_l= 4.3; b) 1982 March 21, m_l=5.0; c) 1988 January 8, m_l=4.1; d) 1992 August 28, m_l=3.8.

were detected.

In conclusion, Fig. 5 summarizes the main spatial features of the seismicity coming from more than ten years of instrumental observations.

Sufficient data exist to compute the focal mechanisms of the earthquakes of March 9, 1980, March 21, 1982 and January 8, 1988. Hypocentres were relocated by LME92, and nodal planes were searched for with the same method as for the shock of August 28, 1992. In this case also, the stability of the solution with respect to the focal depth was successfully checked. The results are shown in Fig. 8, together with the fault plane solution of the August 28, 1992 earthquake.

The hypocenter of the March 9, 1980 earthquake has been relocated at 39.91°N, 16.17°E, and 17 km deep: the nearest settlement is Viggianello, where some permanent macroseismic effects were reported; seventeen polarities are available, two of which do not agree with the geometry of the nodal planes represented in Fig 8. Thirty-nine polarities have been read from seismograms or taken from seismic bulletins for the shock of March 21, 1982, seven of which are discordant with the solution. The focal mechanism of the January 8, 1988 earthquake has been computed using forty-four polarities: in this case the least reliable result was obtained, both because of the percentage of discordant data, attaining the highest value of about 20%, and because of the data distribution over the focal sphere (Fig. 8c).

Focal mechanisms in Fig. 8 share the nodal plane trending at about N45°E, the same strike as the 1988-1989 epicentres. Conversely, the motions at the sources are quite heterogeneous: if the NE-trending nodal plane is assumed to be the fault plane, then Fig. 8 shows a displacement halfway between a dextral transcurrence and a reverse dip slip, a sinistral transcurrence, a normal dip slip, and again a sinistral transcurrence.

CONCLUDING REMARKS

Data available for the western sector of the Calabria-Lucania border, and the adjacent parts of the southern Tyrrhenian Sea, show the existence of several seismogenetic surface structures prone to the release of moderate seismic energy; however in some cases they have been responsible for permanent macroseismic effects. Seismic sources offshore may have a seismic potential greater than those on land.

Due to its relatively low energy level and the physiography of the area, knowledge of this seismicity has to be considered still preliminary. Data available at the moment point to a preferential direction in the space characteristics of the seismic activity. A similar result was obtained by Moretti et al. (1990) on the grounds of mesostructural observations.

The epicentres of the strongest earthquakes in this area over several centuries (Fig. 7) align roughly in the same direction as the microearthquake sequences observed in the last few years. Taking into account their low energy, and the short time interval of instrumental observations, this microseismicity may relate to very local tectonics. The coincidence of present microseismic, and past macroseismic activity however suggests that both reflect the global regional dynamics.

It should be noted that surface geological data confirming recent dynamics for such an inferred structure are not available; nor is this trend evident in satellite imagery (Moretti et al., 1990). In fact, of the two elements dominating the area, the Sangineto Line (Fig. 3) was active as a normal fault from the Messinian to Upper Pliocene, but has been sutured at least since the Mid-Pleistocene (Tortorici, 1981); the Pollino Line, trending NW-SE, allowed left-lateral displacements until the Lower Pleistocene (Ghisetti and Vezzani, 1982), and is presently covered by Mid-Upper Upper Pleistocene deposits, undeformed or crossed by only minor dip-slip faults.

The seismic data lead therefore to the hypothesis that the structures conditioning the present-day deformation are completely buried in such a way that evidence for their existence is not visible at the surface. Alternatively, they may be too recent to have altered the surface geology to a significant degree.

The available geological and seismological information is not yet sufficient to demonstrate the continuity of the structural elements on land and at sea, but they are fully compatible with this hypothesis. If such a continuity does exist, a unique geological structure should begin in the Upper Sinni River (Fig. 3) and extend some 100 km to the south-west, crossing the Pollino Line. At latitude 39.5°N it should reach the Quaternary Palinuro-Cetraro transform fault (Finetti and Del Ben, 1986; Moretti et al., 1990) in an area characterized by submarine volcanic activity. Any reconstruction of the geological evolution of the Tyrrhenian basin and southern Italy should thus pay great attention to the role of such a tectonic element.

Acknowledgement. The Istituto Internazionale di Vulcanologia, Catania, and the Osservatorio Vesuviano, Naples, furnished additional data for calculating hypocentre locations and fault plane solutions. F. Ferrucci critically read the manuscript. This work was financially supported by the Italian Ministry for Universities and Scientific Research. The present paper was partly presented at the 11th Annual Meeting of the National Group of Solid Earth Geophysics, Rome, December 9-11, 1992.

REFERENCES

Baratta M.; 1901: *I terremoti d'Italia*. F.lli Bocca, Torino.

Boccaletti M., Nicolich R. and Tortorici L.; 1984: *The Calabrian Arc and the Ionian Sea in the dynamic evolution of the Central Mediterranean*. Marine Geol., **55**, 219-245.

Branno A., Esposito E., Luongo G., Marturano A., Porfido S. e Rinaldis V.; 1985: *Alcuni terremoti minori del XIX secolo dell' Appennino campano-lucano*. In: Atti 4° Conv. GNGTS, Esagrafica, Roma, pp. 209-219.

Finetti I. and Del Ben A.; 1986: *Geophysical study of the tyrrhenian opening*. Boll. Geof. Teor. Appl., **28**, 75-156.

Ghisetti F. and Vezzani L.; 1982: *The recent deformation mechanisms of the calabrian Arc*. Earth Evol. Sc., **3**, 197-206.

Guerra, I. e Corea I.; 1989: *Sismicità della Calabria negli anni 1986-89*. In: Atti 8° Conv. Ann. GNGTS, Esagrafica, Roma, pp. 41-52.

Guerra I., Moretti A. e Corea I.; 1990: *Microsismicità intermedia e profonda del Tirreno Meridionale: risultati preliminari.* In: Atti 9° Conv. Ann. GNGTS, Esagrafica, Roma, vol. 2, pp. 15-26.

Herrin E.; 1988: *Seismological tables for P.* Bull. Seism. Soc. Am., **58**, 1196-1219.

Istituto Nazionale di Geofisica; 1982: *Bollettino macrosismico*, Roma.

Moretti A., Corea I. e Guerra I.; 1990: *Sismicità attuale e sistemi di fratture superficiali in Calabria.* In: Atti Conv. GNDT, CNR, Pisa, vol. 1, 89-101.

Postpschl D. (ed.); 1985: *Catalogo dei terremoti italiani dall'anno 1000 al 1980.* Quad. Ric. Scient. CNR, 114, vol. 2B, Bologna.

Soloviev S.L., Kuzin I.P., Kovachev S.A., Ferri M., Guerra I. and Luongo G.; 1990: *Microearthquakes in the Tyrrhenian Sea as revealed by joint land and sea-bottom seismographs.* Marine Geol., **94**, 131-146.

Tortorici L.; 1981: *Analisi delle deformazioni fragili dei sedimenti post-orogeni della Calabria Settentrionale.* Boll. Soc. Geol. It., **100**, 291-308.

Wickens A.J. and Hodgson J.H.; 1967: *Computer evaluation of earthquake mechanism solutions.* Publ. Domin. Obs., Ottawa, **33**, pp. 1-10.