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Orientations of the strain main axes in the lithosphere of Sicily and surroundings as deduced from earthquake data

V. CIANCIO [(1)], M. DOLFIN [(1)], D. GILLARD [(2)] and G. NERI [(3)]

[(1)] *Dipartimento di Matematica, Università di Messina, Italy*
[(2)] *Department of Geological and Geophysical Sciences, Princeton University, U.S.A.*
[(3)] *Dipartimento di Fisica della Materia e Tecnologie Fisiche Avanzate Università di Messina, Italy*

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Abstract. Kostrov's method has been used to estimate strain tensor orientations in a rock volume including the lithosphere of Sicily, southern Tyrrhenian and western Ionian. Basic data for the investigation (magnitudes and fault plane solutions of the strongest regional earthquakes) were taken from the literature. We found that most of the study area is characterized by a nearly horizontal north-south maximum shortening similar to that reported by previous investigators for smaller lithospheric volumes in the same area. In addition, our attempts to evaluate the strain orientation uncertainties (the first in the literature for Sicily and surroundings) revealed a level of constraint clearly worse for the minimum shortening axis ε_3 (practically unconstrained in an E-W vertical plane) compared to that found for the maximum shortening axis ε_1. We propose that a roughly north-south Africa-Europe convergence, together with a high degree of structural heterogeneity in the rock volume under investigation, may explain both the ε_1 orientation and the large extent of the confidence area obtained for ε_3. This is in agreement with the available structural maps (indicating the prevailing presence of nearly E-W reverse and NW-SE dextral strike-slip faults) and supports tectonic models locally assuming a low-velocity plate convergence along a direction between NNW-SSE and NNE-SSW.

1. Introduction

Sicily (Fig. 1) is located in the contact belt between the African and European plates (see Scandone and Patacca, 1984, among others). Several tectonic models have been proposed for the entire Italian region and the debate on this topic is still open. Northwestward active subduction

Corresponding author: G. Neri; Dipartimento di Fisica della Materia e Tecnologie Fisiche Avanzate, University of Messina, Via dell'Osservatorio 4, 98121 Messina, Italy; tel. +39 90 360101; fax +39 90 363533; e-mail: geoforum@imeuniv.unime.it

beneath the southern Tyrrhenian was suggested by Barberi et al. (1973), passive subduction by Patacca et al. (1990), rifting in the southwestern Tyrrhenian by Finetti and Del Ben (1986), mantle diapir growth in the whole Tyrrhenian by Locardi (1988), and prevailing transcurrent dynamics controlled by north-south plate convergence by Boccaletti et al. (1990). In the different models the plate convergence velocity at the longitude of Italy ranges from negligible (see Locardi, 1988) to fairly low (1 cm/yr according to De Metz et al., 1990; Pollitz, 1991) and oriented between NNW (De Metz et al., 1990) and NNE (Mantovani et al., 1990, 1992). The variety of opinions is mostly due to the high complexity of the area, which is characterized by strong heterogeneity of lithospheric structure and strain style. Most information concerning strain comes from geological studies. In a very first approximation, three main domains may be recognized: Sicily (mainly showing N-S contraction; Ben-Avraham and Grasso, 1990), the Appenines (extension roughly orthogonal to the chain; Cristofolini et al., 1985; Cinque et al., 1993) and the Alps (N-S contraction; Castellarin et al., 1992) (Fig. 1). On a smaller scale, Sicily is characterized by some degree of heterogeneity. Northeastern Sicily, which is the southern edge of the Calabrian Arc Appeninic structure, shows mostly extensional tectonics (Ghisetti, 1984; Cristofolini et al., 1985; Bousquet et al., 1987; the main normal faults and graben structures are reported in Fig. 1). Contraction is dominant in the remaining part of Sicily, where dextral strike-slip and reverse faults of varying orientation are present (Finetti and Del Ben, 1986; Ben-Avraham et al., 1990) (Fig. 1).

The present-day state of strain in the intermediate and deep crust cannot be easily investigated by surface geology which, on the other hand, gives a picture of tectonic processes over long time intervals. Seismic data are often a good marker of the present tectonics and, depending on the earthquake sample available, may give a reliable picture of strain in rock volumes including also deep structures. A limitation of seismic methods is that they do not take into account aseismic deformation, which may be important (Jackson and Mc Kenzie, 1988). Therefore, adding strain information derived from seismic data to what we know from geology may help to obtain a more complete view of tectonic processes. In Sicily, seismic methods for strain computations have been applied by Albarello et al. (1991), Westeway (1992) and Kiratzi (1994). Westeway's (1992) analysis was marginal to the Sicilian area, as the author focused on the Appenine region and, therefore, only part of northeastern Sicily was included in his investigation. Kiratzi (1994) derived the strain and velocity tensors from moment and fault plane solutions of six crustal $M \geq 5$ earthquakes, the location of which (see Fig. 2 and caption of Fig. 3) led the author to investigate part of western Sicily and of the southern Tyrrhenian. A nearly NNE-SSW shortening was proposed, without information on uncertainties of estimated strain orientations. Strain computations in a large E-W Mediterranean belt were performed by Albarello et al. (1991), who found a north-south shortening in northwestern Sicily. No error analysis was reported even in this case.

Concerning tectonic stress distribution, Caccamo et al. (1996) found that a volume can be defined which includes part of the lithosphere of Sicily, the southernmost Tyrrhenian and the westernmost Ionian (sector C in Fig. 1), where stress is homogeneous. In particular, the application of Gephart and Forsyth's (1984) method allowed the authors to obtain a shallowly south-plunging σ_1 (maximum compressive stress) with a value of 0.9 for the R parameter $(\sigma_1\text{-}\sigma_2)/(\sigma_1-\sigma_3)$, indicating that amplitudes of the intermediate and minimum compressive stresses are nearly

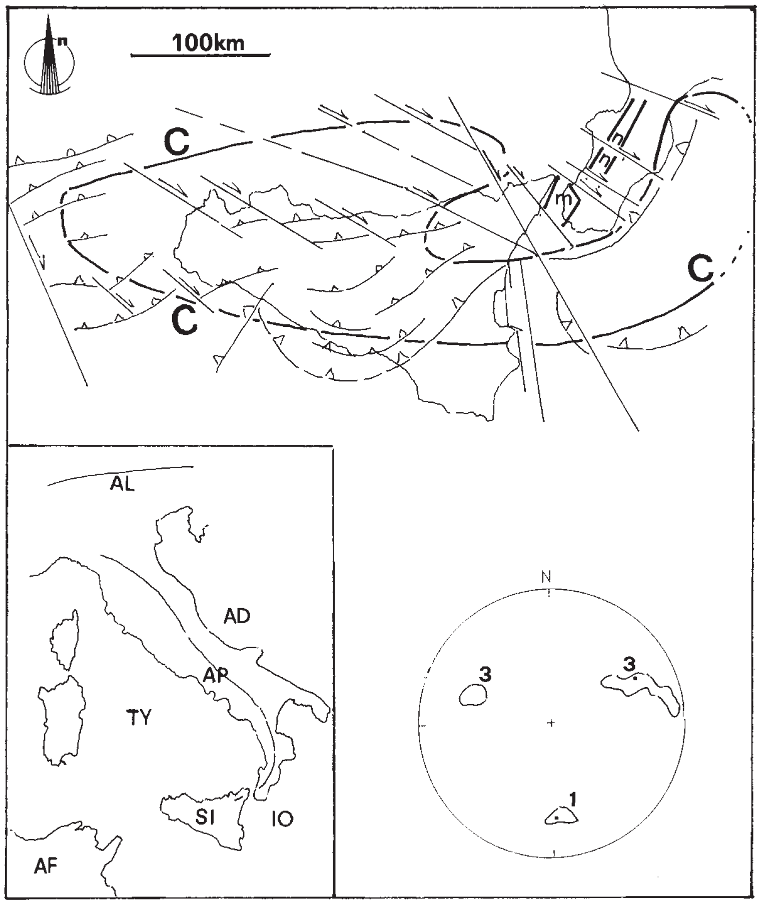

Fig. 1 - Map of Sicily and surroundings, with the trace of the lithospheric volume investigated by Caccamo et al. (1996) for stress distribution (thick curved line, C) and the main faults (redrawn from Cristofolini et al., 1985 and Finetti and Del Ben, 1986). Arrows and dented symbols indicate strike-slip and reverse faults, respectively. Segments without symbols indicate normal faults. The main graben structures in southern Calabria and northeastern Sicily (Messina and Mesima grabens) are indicated by letters m and n, respectively. AF, SI, AP, AL, TY, AD, and IO stand for Africa, Sicily, the Appenines, Alps, Tyrrhenian, Adriatic and Ionian. Curved lines in the inset indicate the location of the main mountain chains in the Italian peninsula (Alps and Appenines). The confidence areas of the maximum (1) and minimum (3) compressive stress orientations in volume C (as computed by Caccamo et al., 1996) are also reported. Dots inside the confidence areas indicate the best stress solution.

equivalent. The average angular discrepancy between fault-plane solutions and stress model resulted very low (average misfit F=3.1°) with the individual misfits of all sector C earthquakes smaller than uncertainties of the respective fault parameters. However, when earthquakes of the Calabrian Arc were added to the set relative to volume C, stress inversion led to a fairly large average misfit (8.6°), revealing some degree of stress heterogeneity and therefore showing that the stress regime in the Calabrian Arc is different from that in volume C.

Starting from the above information and considerations, we decided to use seismic data in order to estimate orientations of the strain main axes in the area shown in Fig. 1. Our study area is significantly larger than sectors investigated in the previously published seismic strain studies. We also propose in the present work the first attempt in the literature to evaluate uncertainties of

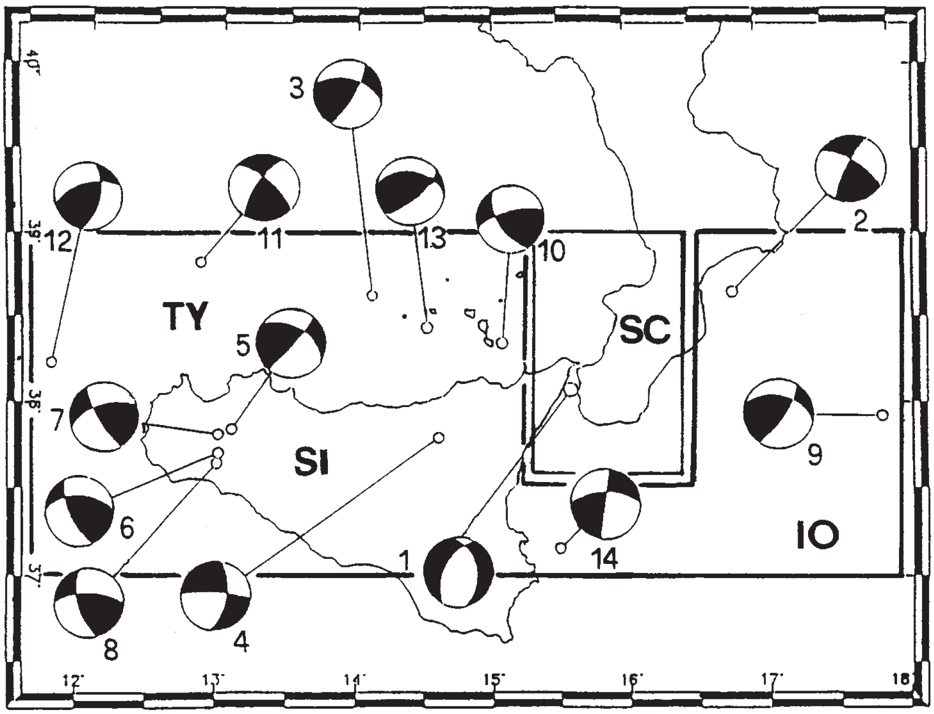

Fig. 2 - Fault plane solutions of earthquakes used for computing strain orientations in the present work. The lower hemisphere projection is adopted. Black and white quadrants mean compression and dilatation, respectively. Numbering of events corresponds to that in Table 1. The figure shows the study volume subject to N-S contraction, including part of Sicily (SI), Tyrrhenian (TY) and Ionian (IO) (thick line), and the volume including southern Calabria and northeastern Sicily (SC) involved in extensional processes (thin line).

strain orientations in the study area, and a comparison of stress and strain orientations. Finally, our findings concerning strain tensor orientations are compared with strain data coming from geological studies and with knowledge on the local geodynamics.

2. Method

The algorithm used for computing strain parameters and their uncertainties was derived from Kostrov's method (1974), and is widely described in Gillard et al. (1992) and Wyss et al. (1992). Basic data are earthquake magnitudes and fault plane solutions. Magnitude M_S is converted in the scalar moment M_O by a proper relationship which, in our case, is log M_0=1.5 M_S+16.27 (Kiratzi, 1994). Other moment-magnitude relationships proposed in the literature for the same region (e.g. Giardini et al., 1984) are not appreciably different from Kiratzi's (1994) in relation to our purpose. The scalar moment M_0^k of each earthquake is combined with its fault plane solution in order to obtain the moment tensor M_{ij}^k of the event. The moment tensors of all the available events are used for the computation of the strain tensor elements ε_{ij}, after having assigned numerical values to the shear modulus μ and the rock volume considered V (Kostrov,1974):

In our case, μ and V were assumed to be $3 \cdot 10^{10}$ dyn/cm^2 and $9.6 \cdot 10^{20}$ cm^3, respectively. Values

$$\varepsilon_{ij} = \frac{1}{2\mu V}\sum_k M_{ij}^k \tag{1}$$

assigned to shear modulus and volume do not, however, influence the orientation of the strain principal axes.

Uncertainties of computed strain parameters were estimated using a procedure described by Wyss et al. (1992) based on use of the covariance matrix formalism. In this approach, error computations are performed by assuming that (1) there are no systematic errors and (2) the errors of the scalar moment, strike and dip are independent of each other. Standard deviations D_{ij} of the strain tensor components ε_{ij} are estimated by considering that ε_{ij} is a function of the scalar moment M_0^k, strike ϕ^k, dip δ^k and rake λ^k, with k identifying the generic earthquake of the set available. The covariance matrix D_{ij} of the strain can be written as
where A^k is the derivative matrix

$$D_{ij} = \sum_k A^k D_0 A^{k^T} \tag{2}$$

and T signifies the transpose. D_0 is the initial covariance matrix written as

$$A^k = \begin{bmatrix} \frac{\partial\varepsilon_{xx}}{\partial M_0^k} & \frac{\partial\varepsilon_{xx}}{\partial\phi^k} & \frac{\partial\varepsilon_{xx}}{\partial\delta^k} & \frac{\partial\varepsilon_{xx}}{\partial\lambda^k} \\ \frac{\partial\varepsilon_{xy}}{\partial M_0^k} & \frac{\partial\varepsilon_{xy}}{\partial\phi^k} & . & . \\ \frac{\partial\varepsilon_{xz}}{\partial M_0^k} & \frac{\partial\varepsilon_{xz}}{\partial\phi^k} & . & . \\ \frac{\partial\varepsilon_{yy}}{\partial M_0^k} & \frac{\partial\varepsilon_{yy}}{\partial\phi^k} & . & . \\ \frac{\partial\varepsilon_{yz}}{\partial M_0^k} & \frac{\partial\varepsilon_{yz}}{\partial\phi^k} & . & . \\ \frac{\partial\varepsilon_{zz}}{\partial M_0^k} & \frac{\partial\varepsilon_{zz}}{\partial\phi^k} & . & \frac{\partial\varepsilon_{xx}}{\partial\lambda^k} \end{bmatrix} \tag{3}$$

where ΔM_0^k, $\Delta\phi^k$, $\Delta\delta^k$ and $\Delta\lambda^k$ are the standard deviations of the scalar moment, azimuth, dip and

$$D_0 = \begin{bmatrix} \left(\Delta M_0^k\right)^2 & 0 & 0 & 0 \\ 0 & \left(\Delta\phi^k\right)^2 & 0 & 0 \\ 0 & 0 & \left(\Delta\delta^k\right)^2 & 0 \\ 0 & 0 & 0 & \left(\Delta\lambda^k\right)^2 \end{bmatrix} \tag{4}$$

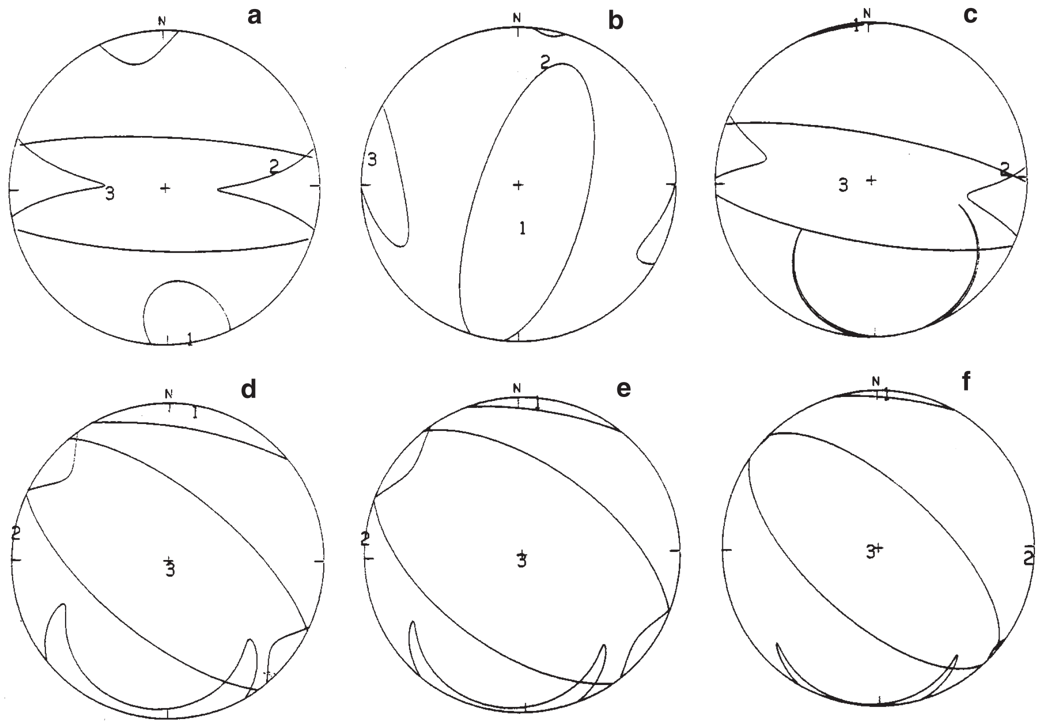

Fig. 3 - 95% confidence areas of the maximum (1) and minimum (3) compressive strain orientations, with symbols 1 and 3 indicating the respective solutions obtained by Kostrov's (1974) method. The orientation of the intermediate compressive strain axis is reported (2) without confidence limits.
a) Set ''CALEXCLU'' (events 2 to 14; Fig. 2 and Table 1).
b) ''ALL'' (1 to 14).
c) ''SOUTH'' (3 to 10 and 12 to 14).
d) ''WEST'' (3 to 8 and 10 to 13).
e) ''WESTMOD'' (3 to 8, 10, 12 and 13).
f) ''KIRATZI'' (6 to 8, 10, 12 and 13).

rake, respectively. Their average values for each event in a dataset are used (Wyss et al., 1992). Then, based on the process of solving for principal strains (S_i; i=1, 2, 3) and their direction cosines (C_i; i=1, 2, 3), the same procedure is applied again in order to compute standard deviations of S_i and C_i, by assuming ε_{ij} as independent variables and S_i, C_i as dependent variables. The accuracy of this procedure is a function of how well assumptions (1) and (2) are fulfilled. Testing alternative procedures (such as Monte Carlo) may be appropriate and we are working in this direction. In any case, the computation reported here of uncertainties of strain parameters, although preliminary, is meaningful, also because it is the first carried out for the study area.

3. Data and analysis

The earthquake data used in this study are reported in Table 1 and Fig. 2. This dataset includes only fault-plane solutions taken from the literature. The solutions were selected by

Table 1 - Earthquake data used for computing strain orientations. Order number, date, origin time, epicenter latitude and longitude, focal depth, magnitude, azimuth and dip of both nodal planes, rake, weight factor and bibliographic source are reported for each event. Weights W assigned to fault plane solutions were taken from Caccamo et al. (1996) who carried out a critical evaluation of the quality of information from the literature.

N	Date	O.T.	Lat	Lon	Depth	M	az1	dip1	az2	dip2	rake	W	bibl.
01	1908 12 28	04:20	38.12	15.60	10	7.0	208	55	349	42	046	2	G2
02	1947 05 11	06:22	38.69	16.78	14	5.6	302	68	206	77	014	1	G2
03	1957 05 21	11:44	38.67	14.11	05	5.3	030	74	286	50	042	1	G5
04	1967 10 31	21:08	37.84	14.60	38	5.0	089	61	273	80	016	2	G2
05	1968 01 15	01:33	37.89	13.08	20	5.1	040	82	302	46	044	1	G2
06	1968 01 15	02:01	37.75	12.98	10	5.4	270	50	156	64	035	2	AJ
07	1968 01 16	16:42	37.86	12.98	36	5.1	250	58	150	75	018	2	AJ
08	1968 01 25	09:56	37.69	12.97	03	5.1	270	64	165	62	031	2	AJ
09	1968 02 12	10:18	37.96	17.87	10	5.2	034	72	284	43	050	1	G5
10	1978 04 15	23:33	38.39	15.07	21	5.5	148	55	254	68	153	2	AJ
11	1979 01 20	13:49	38.87	12.86	04	5.2	312	68	214	70	016	2	G5
12	1979 12 08	04:06	38.28	11.74	33	5.4	254	56	012	55	136	2	AJ
13	1980 05 28	19:51	38.48	14.52	12	5.7	052	62	278	37	064	2	AJ
14	1990 12 13	00:24	37.20	15.50	10	5.4	008	90	270	60	031	2	G9

G2= Gasparini at al. (1982)
G5= Gasparini at al. (1985)
AJ= Anderson and Jakson (1987)
G9= Giardini at al. (1993)

Caccamo et al. (1996) after a critical evaluation of the information quality, and were assigned a weight (1 or 2). Only events of magnitude M≥5 were considered in order to focus on processes of regional relevance.

We computed strain parameters for the whole set of Table 1 and Fig. 2 (set ALL) and for several subsets of it, including a minimum of six events:

- Subset CALEXCLU: the 1908 earthquake (N. 1 in Fig. 2 and Table 1) occurred in the Messina graben (Fig. 1) and was related to tensional dynamics of the Calabrian Arc Appeninic structure (Bottari et al., 1989). Therefore, this event was located in a different tectonic domain with respect to events available to the west. The tectonic situation to the east (Ionian Sea) is less clearly stated but we know that stress is homogeneous over the whole sector covered by CALEXCLU events (Caccamo et al., 1996).

- Subset SOUTH: the two nothernmost events in the Tyrrhenian and the Ionian (N. 11 and 2 in Fig. 2) were escluded from CALEXCLU.

- Subset WEST: all Ionian events (N. 2, 9 and 14) were excluded from CALEXCLU with the purpose of isolating the western Sicily compressive domain.

- Subset WESTMOD: the northernmost event (N. 11) was excluded from WEST.

- Subset KIRATZI: this is the set used for strain computations by Kiratzi (1994) (events N. 6, 7. 8, 10, 12 and 13 in Fig. 2).

The orientations of the strain principal axes estimated from all these sets are reported in Fig. 3 and Table 2.

4. Discussion

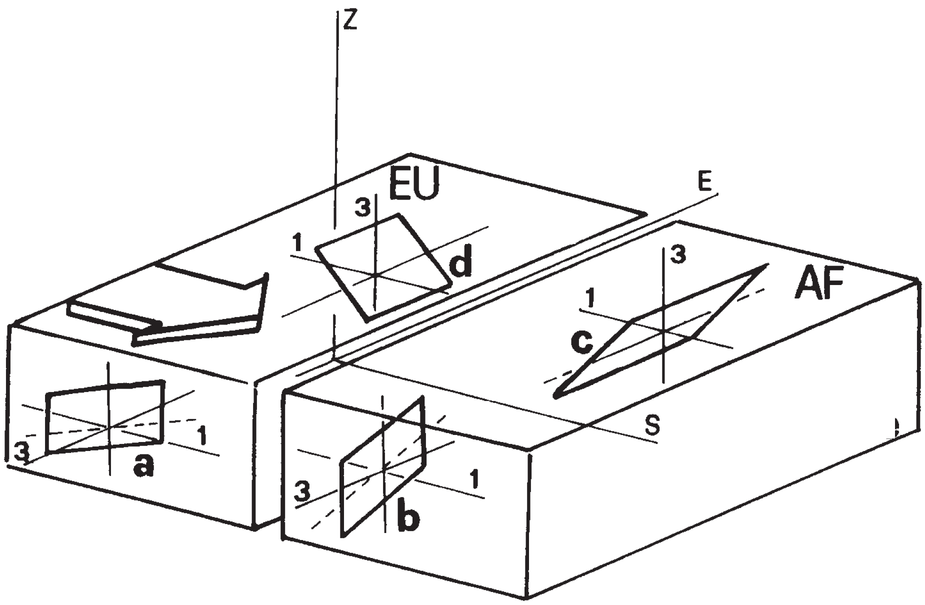

Fig. 4 - This scheme proposes an explanation of strain results obtained from the earthquake set CALEXCLU (Figs. 3a and 2). The arrow indicates the north-south relative motion of the African (AF) and European (EU) plates. Several faults of different orientation are postulated in the contact area between the respective plates (a: NW-SE vertical strike-slip fault; b: NE-SW vertical strike-slip fault; c: 45° northward-dipping reverse fault; d: 45° southward-dipping reverse fault). Symbols 1 and 3 indicate the orientations of the max. and min. compressive strain for all faults. Thus, the situation described in this figure may justify the computed orientations of the max. and min. compressive strains, as well as the different level of constraint of the respective solutions in Fig. 3a. Our result is in agreement with Finetti and Del Ben's (1986) regional structural map (see also Fig. 1) and supports tectonic models locally assuming a low-velocity plate convergence along a direction between NNW-SSE and NNE-SSW.

The 95% confidence areas for the ε_1 and ε_3 orientations obtained from set CALEXCLU show that the orientation of ε_1 is better constrained than that of ε_3 (Fig. 3a). The solution (1, 2 and 3 stand for ε_1, ε_2 and ε_3) indicates maximum shortening oriented north-south, similar to the N-S maximum compression inferred from stress inversion in the same area by Caccamo et al. (1996; see also Fig. 1). The maximum extension axis (3 in Fig. 3a) is practically unconstrained in a nearly E-W vertical plane. It may also be observed in Fig. 1 that the maximum compressive stress orientation is fairly well constrained, diversely from the minimum compressive stress orientation. This may be related to the high value of R (0.9), meaning that the amplitudes of the minimum and intermediate compressive stresses are nearly equivalent (see Introduction). A comparison between stress and strain orientations, as reported in Figs. 1 and 3a, respectively, reveals a fairly good correspondence, showing that fault planes are preferentially inclined at about 45° with respect to the maximum compressive stress (the reader interested in a detailed treatment of aspects concerning the relative orientation of stress, strain and seismic dislocation surfaces may refer to Wyss et al., 1992).

When the 1908 earthquake is included (set ALL, Fig. 3b) its contribution to strain

Table 2 - Numerical values in degrees of azimuth and dip relative to the strain principal axes (1, 2 and 3 stand for max-

imum, intermediate and minimum compressive strain, respectively) obtained for all earthquake sets investigated in the present work. Identification letters a to f correspond to those in Fig. 3.

computation is dominant, because its magnitude value (7) is clearly larger than all others in the

Id letter	Set	1	2	3
a	CALEXCLU	171 03	080 28	266 61
b	SICILY	173 68	013 21	280 07
c	SOUTH	356 01	086 14	262 76
d	WEST	010 04	280 02	162 85
e	WESTMOD	007 03	277 01	170 87
f	KIRATZI	004 02	094 03	243 86

sample (5 to 6), and the resulting deformation style is strongly conditioned by the normal faulting mechanism of this event. The results reported in Fig. 3c-f for the other sets investigated do not appear much different from those relative to CALEXCLU (Fig. 3a), even though the confidence areas in 3c-f are slightly larger than in Fig. 3a. In particular, the confidence areas of ε_1 and ε_3 for all subsets Fig. 3c to f (SOUTH, WEST, WESTMOD, KIRATZI) show some overlap, and this situation is not observed for CALEXCLU. We propose that there is some degree of strain homogeneity over the volume covered by CALEXCLU earthquakes (thick line in Fig. 2), but reducing the extent of the study volume (c to f) enlarges strain uncertainties as a consequence of decrease in the number of events available for computations.

We conclude that the nearly N-S shortening proposed for western Sicily by previous investigators (Albarello et al., 1991; Kiratzi, 1994) concerns a significantly larger lithosphere volume (thick line in Fig. 2), including also the southernmost Tyrrhenian and the westernmost Ionian. It is also noteworthy that strain information coming from surface geology of Central and Western Sicily (Ben-Avraham and Grasso, 1990) is confirmed by our strain investigation based on the analysis of seismic events located at all depth levels in the crust. Concerning Fig. 3a, some degree of structural heterogeneity may justify the spreading of the ε_3 confidence area, in the framework of a roughly north-south Africa-Europe convergence explaining the σ_1 and ε_1 orientations. In particular, the coexistence of E-W reverse faults with NW-SE and NE- SW vertical transcurrent faults can produce the effects observed in terms of strain tensor orientation (such a situation is schematized in Fig. 4). This scheme is compatible with Finetti and Del Ben's (1986) regional structural map (see also Fig. 1) which indicates the dominant presence of nearly E-W reverse and NW-SE dextral strike-slip faults. In other words, our findings concerning the orientations of the strain main axes in the area 37°-39° N, 11°-18°E support tectonic models locally assuming a non-negligible plate convergence velocity, even though extensional processes appear to be dominant in part of the study area (southern Calabria, thin line in Fig. 2). Extensional processes along the whole Appenine chain (Fig. 1) including Calabria, have been recently explained as due to eastward roll-back of a westward dipping Adriatic-Ionic subduction slab, with roll-back occurring faster than north-south plate convergence (Cinque et al., 1993; Neri, 1994). In any case, extension in southern Calabria (thin line in Fig. 2) cannot be considered as a very localized situation, and this is also shown by the amount of seismic energy released in the normal faults of the whole Appeninic chain, clearly greater than in all the confining compressive domains (Neri, 1994).

5. Conclusions

The application of Kostrov's (1974) method to magnitudes and fault plane solutions of the strongest earthquakes of Sicily, southern Calabria, the southernmost Tyrrhenian and the westernmost Ionian, has allowed us to state that a large portion of the study area (indicated by a thick line in Fig. 2) is characterized by a nearly horizontal north-south maximum compressive strain similar to that reported by previous investigators relative to smaller lithosperic volumes in the same region (e.g. Western Sicily). Extensional processes are, however, dominant in a part of the study area, southern Calabria (thin line in Fig. 2), which represents the southern edge of the Appeninic extensional domain. The number of events available in the N-S contraction domain allowed us to check the stability of strain results by investigating several earthquake subsets corresponding to different rock sub-volumes. In addition, computations made to evaluate the strain orientation uncertainties (the first in the literature for the study area) revealed a level of constraint that was clearly worse for the minimum shortening axis ε_3 (practically uncontrained in a E-W vertical plane) than for the N-S maximum shortening axis ε_1.

Our strain investigation, based on the analysis of seismic events located at all depths in the crust, confirms strain information coming from surface geology. The orientations found of the strain main axes are in agreement with structural maps indicating nearly E-W reverse and NW-SE dextral strike-slip faults, and support tectonic models assuming an Africa-Europe slow convergence along a direction between NNW-SSE and NNE-SSW at Italian longitudes in the Mediterranean belt. Extension in southern Calabria is not a localized situation, being part of extensional processes involving the whole Appeninic chain, and was recently explained as due to eastward roll-back of a westward dipping Adriatic-Ionic subduction slab, with roll-back occurring faster than north-south plate convergence (Cinque et al., 1993; Neri, 1994).

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