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Finite element modelling of the recent-present deformation pattern in the Calabrian arc and surrounding regions

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Abstract
An attempt is made to quantify the implications of the hypothesis that the recent-present deformation pattern in the Calabrian arc and the adjacent African margin is mainly determined by horizontal tectonic forces induced by the relative convergence of the confining blocks (Africa and Adriatic). Modelling of present-day tectonic processes is carried out by means of a 2D finite element scheme involving elastic shells in a plane stress approximation. On the assumption that tectonic processes are strongly influenced by the presence of major discontinuities, the model includes zones where most deformations can concentrate. Convergent and divergent boundaries are simulated by narrow belts having elastic parameters lower than those in the surrounding regions. Transform boundaries are reproduced by orthotropic elements. Kinematic boundary conditions are imposed to simulate the relative convergence between Africa and the Adriatic. Numerical experiments show that this convergence causes the lateral escape of crustal wedges in the Calabrian arc and the adjacent African margin (Sicily). The resulting microplate kinematics can account for the complex distribution of compressional, tensional and transcurrent deformations actually observed.

Key words *geodynamic modelling – finite elements – Mediterranean*

1. Introduction

The easternmost sector of the Maghrebian belt, with the related Iblean foreland zone, and the Calabrian arc (fig. 1) has been affected by intense tectonic activity during the recent evolution, as indicated by neotectonic deformations, intense seismicity and volcanism (see, *e.g.*, Barbano *et al.*, 1978; Beccaluva *et al.*, 1982; Cristofolini *et al.*, 1985; Finetti and Del Ben, 1986; Bigi *et al.*, 1989; Van Dijk and Okkes, 1991; Reuther *et al.*, 1993).

The distribution of recent (Quaternary) compressional, tensional and transcurrent features delineates a strong lateral heterogeneity of the strain field. The central sector of the Sicily Channel has been affected by a SW-NE extension in the framework of strike slip tectonics (see, Cello *et al.*, 1985; Finetti and Del Ben, 1986). Sinistral transpressional movements are observed along the Egadi fault (EF in fig. 1) separating the Adventure block (AD) from the adjacent Maghrebian belt (Reuther *et al.*, 1993), and along the Sciacca fault (SF), between the Adventure block and the Gela basin (GB). A system of dextral transform faults (Comiso-Scicli, CF) is observed at the boundary between the Iblean block (IB) and the Gela basin (Antonelli *et al.*, 1988; Argnani *et al.*,

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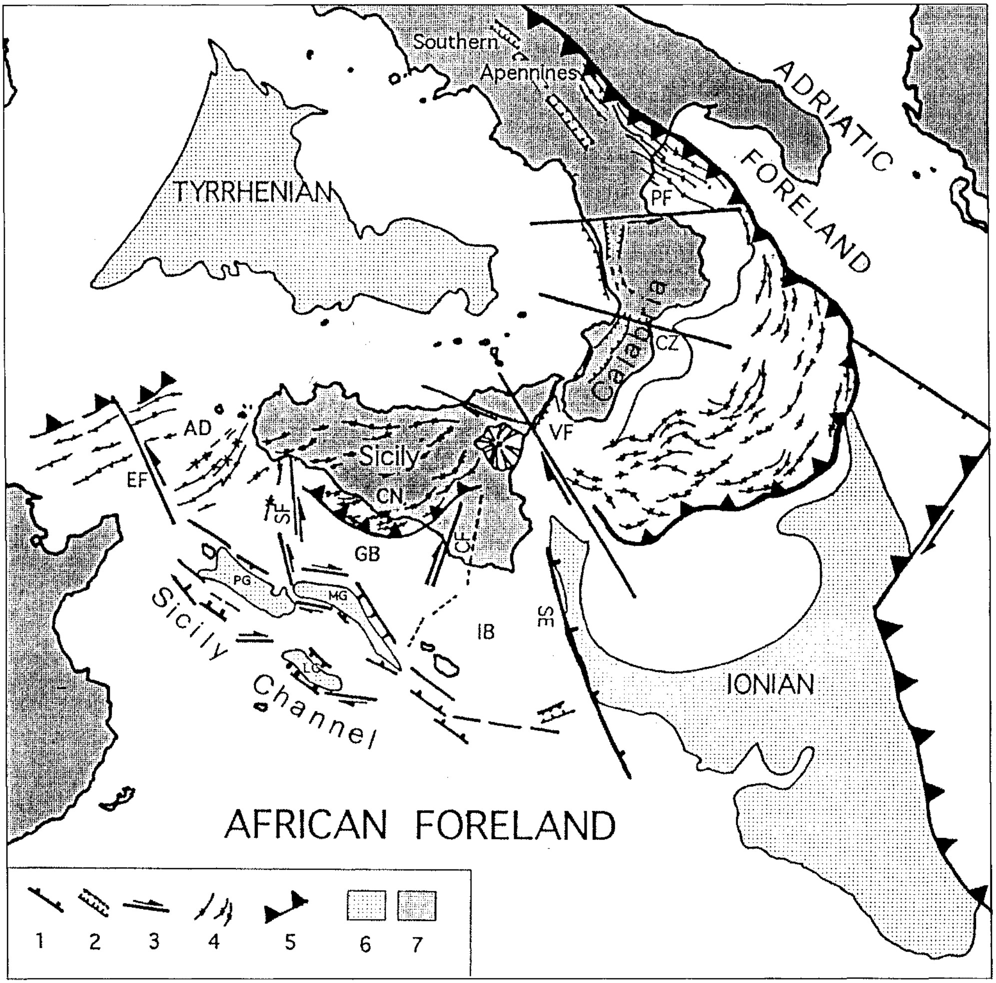

Fig. 1. Tectonic sketch of the zone considered (from Finetti and Del Ben, 1986; Reuther *et al.*, 1993 modified). 1) Escarpments; 2, 3, 4) major tensional, transcurrent and compressional features; 5) thrust fronts; 6) Tyrrhenian and Ionian bathial plains and troughs in the Sicily Channel; 7) emerged lands. AD = Adventure plateau; SF = Sciacca fault; CF = Comiso-Scicli fault; EF = Egadi fault; GB = Gela block; VF = Vulcano fault; CN = Caltanissetta nappe; CZ = Catanzaro fault; IB = Iblean plateau; LG = Linosa graben; MG = Malta graben; PF = Palinuro fault; PG = Pantelleria graben; SE = Syracuse escarpment.

1987; Reuther *et al.*, 1993). Compressional deformation, roughly oriented SSE-NNW, has affected the Caltanissetta nappe (CN), overthrusting the Gela basin (see, Cristofolini *et al.*, 1985; Ben Avraham and Grasso, 1990). The Syracuse escarpment (SE), whose present activity is not clearly recognized, represents a morphological-structural boundary between the Iblean continental shelf and the thinned Ionian basin. Dextral transpressional activity along the Vulcano fault (VF), allowing the relative motion between the Calabrian arc and the Iblean block is recognized (Finetti and Del Ben, 1986). A sinistral shear along the Palinuro fault system (PF) has decoupled the Calabrian arc from the Southern Apennines (Finetti and Del Ben, 1986; Cello *et al.*, 1985; Reuther, 1990; Van Dijk and Okkes, 1991). Other transform faults have been active in Calabria (Ghisetti and Vezzani, 1982; Knott and Turco, 1991; Del Ben, 1993), one of the most important of which seems to be the Catanzaro fault (CZ). A SE-NW to E-W extensional regime has affected the Tyrrhenian margin of Calabria (Barone *et al.*, 1982; Del Ben, 1993). Compressional deformations are recorded in the external Calabrian arc, offshore the Ionian coast of Calabria. This feature is interpreted as an effect of the overthrusting of the Calabrian wedge over the thinned Ionian foreland (Rossi and Sartori, 1981; Barone *et al.*, 1982; Del Ben, 1993).

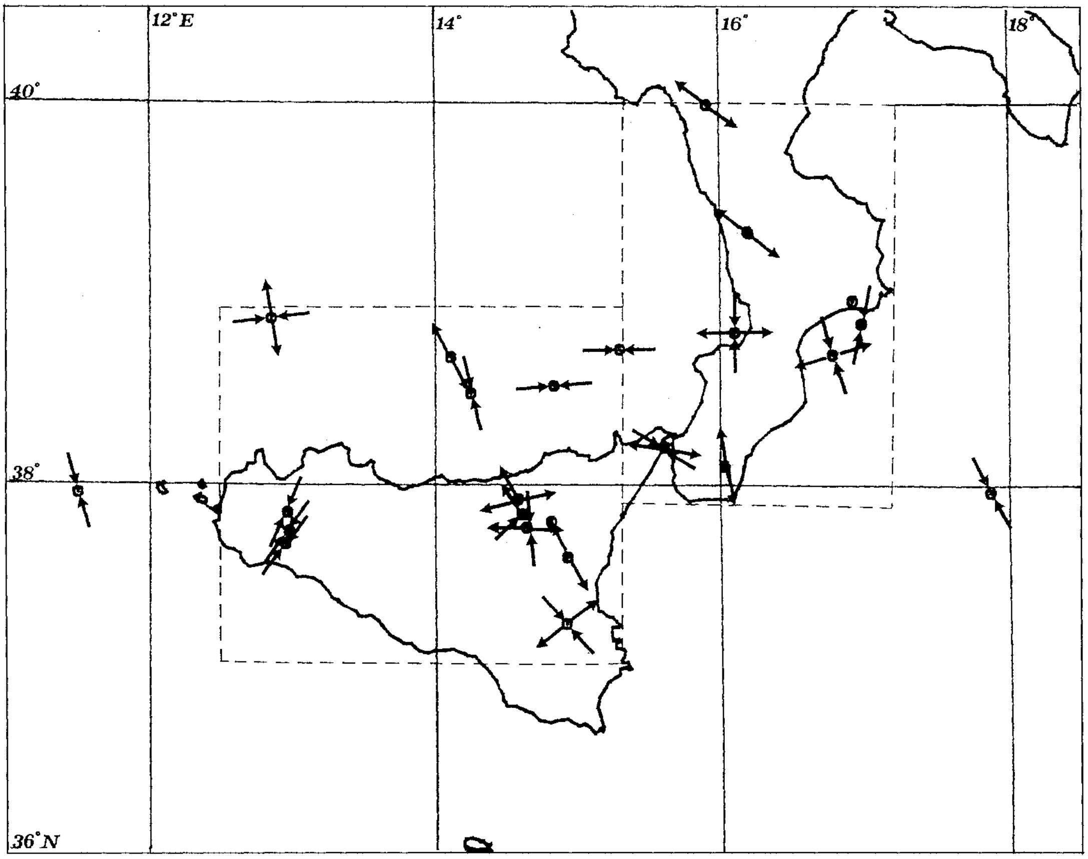

Fig. 2. Fault plane solutions of shallow earthquakes ($h \leq 50$ km) in the study area (Riuscetti and Schick, 1975; D'Ingeo *et al.*, 1980; Gasparini *et al.*, 1982, 1985; Giardini *et al.*, 1984; Hfaiedh *et al.*, 1985; Benina *et al.*, 1985; Anderson and Jackson, 1987; Westaway, 1987; Udias *et al.*, 1989; Dziewonski *et al.*, 1985, 1987a,b,c, 1991a,b). The horizontal projections of *T* and *P* axes are respectively represented by diverging and converging arrows. Only axes dipping less than 30° are reported. Dashed lines identify the boundaries of the «Calabria» and «Sicily» zones, which have been considered for the analysis of stress and strain fields (table I).

As concerns the present-day tectonic pattern, stress and strain field data can be obtained by the analysis of earthquake fault plane solutions, since few and contrasting indications are provided by *in-situ* stress measurements (Grasso *et al.*, 1986; Bousquet *et al.*, 1988). Figure 2 shows the available fault mechanisms of shallow earthquakes (≤ 50 km) in the area here considered. The distribution of these data is not homogeneous, most earthquakes are located inland along the Tyrrhenian coast of Calabria and in Sicily. Figure 2 shows, for each earthquake, the horizontal projection of P and T directions, which can be considered representative of the local maximum and minimum principal strain axis respectively (Marrett and Allmendinger, 1990). In Calabria, earthquakes along the Tyrrhenian coast show normal mechanisms, while dextral strike-slip mechanisms are observed along the Catanzaro fault. Only one fault plane solution, indicating a thrust mechanism, is available along the Calabrian-Ionian front. Western Sicily shows coherent thrust mechanisms both inland and offshore. All these indications are compatible with the quaternary deformation pattern shown in fig. 1. Four out of five available fault plane solutions related to shallow seismicity in the Tyrrhenian basin show a compressive character. Assuming that local faulting is controlled by large scale dynamics, the integrated analysis of seismic sources belonging to a given crustal block can supply information on the regional strain and stress fields (see, *e.g.*, Jackson and McKenzie, 1988; Wyss *et al.*, 1992). To this purpose, some standard numerical techniques (Kostrov, 1974; Gephart and Forsyth, 1984; Marrett and Allmendinger, 1990; Carey-Gahilardis and Vergely, 1992) have been applied to earthquakes occurred in the two regions shown in fig. 2, which have been tentatively assumed as homogeneous. The results obtained by this analysis (table I and fig. 3) indicate that both Sicily and Calabria are affected by a N-S to NNW-SSE compressive field, associated with an E-W to WNW-ESE tensional field, in line with neotectonic data (Barbano *et al.*, 1978; Philip, 1983; Lo Giudice and Rasà, 1986; Van Dijk and Okkes, 1991) and VLBI measurements (Zarraoa *et al.*, 1994; Lanotte *et al.*, 1995) which indicate shortening between the Iblean block and Apulian foreland. By assuming a thickness of the seismic layer of the order of 10^4 m, as indicated by the distribution of available hypocentral depths, an average rigidity of the order of $3 \cdot 10^{10}$ Pa and a time interval of 100 years, Kostrov's approach gives values of the order of 10^{-16} s^{-1} and 10^{-18} s^{-1} (10^{-9} and 10^{-11} yr^{-1} respectively) for seismic strain rates in Calabria and Sicily respectively. Some geodynamic hypotheses have been advanced to explain the complex deformation pattern discussed above and, in particular, its most striking feature, *i.e.* the presence of tensional strains in a small sector, the Sicily Channel, of the Africa collisional boundary in the Mediterranean region. Some authors (Illies, 1981; Beccaluva *et al.*, 1983; Ben Avraham and Grasso, 1990; Reuther *et al.*, 1993) suggested that the

Table I. Orientations (strike and dip in degrees) of maximum and minimum strain and stress axes in Calabria and Sicily deduced from focal mechanisms (strike direction is reported with respect to north and dip is from the horizontal plane). The two estimates (a and b) of principal strain axes for each zone have been respectively obtained by the procedures proposed by Marrett and Allmendinger (1990) and by Kostrov (1974). For the application of this last technique an empirical relationship between scalar moment tensor and surface wave magnitude (see, *e.g.*, Jackson and McKenzie, 1988) has been adopted in the cases in which a direct estimate of seismic moment is not available. The two estimates (c and d) of principal stress axes for each zone have been respectively obtained by the procedures proposed by Carey-Gailhardis and Vergely (1992) and by Gephart and Forsyth (1984). As concerns this last approach, the contribution of single fault plane solutions has been weighted linearly with magnitude.

		Sicily		Calabria	
Strain		ε_1	ε_3	ε_1	ε_3
	a	228/28	115/38	171/52	283/16
	b	193/-5	108/42	184/34	92/1
Stress		σ_1	σ_3	σ_1	σ_3
	c	207/17	90/38	207/17	248/33
	d	359/9	268/8	321/80	87/6

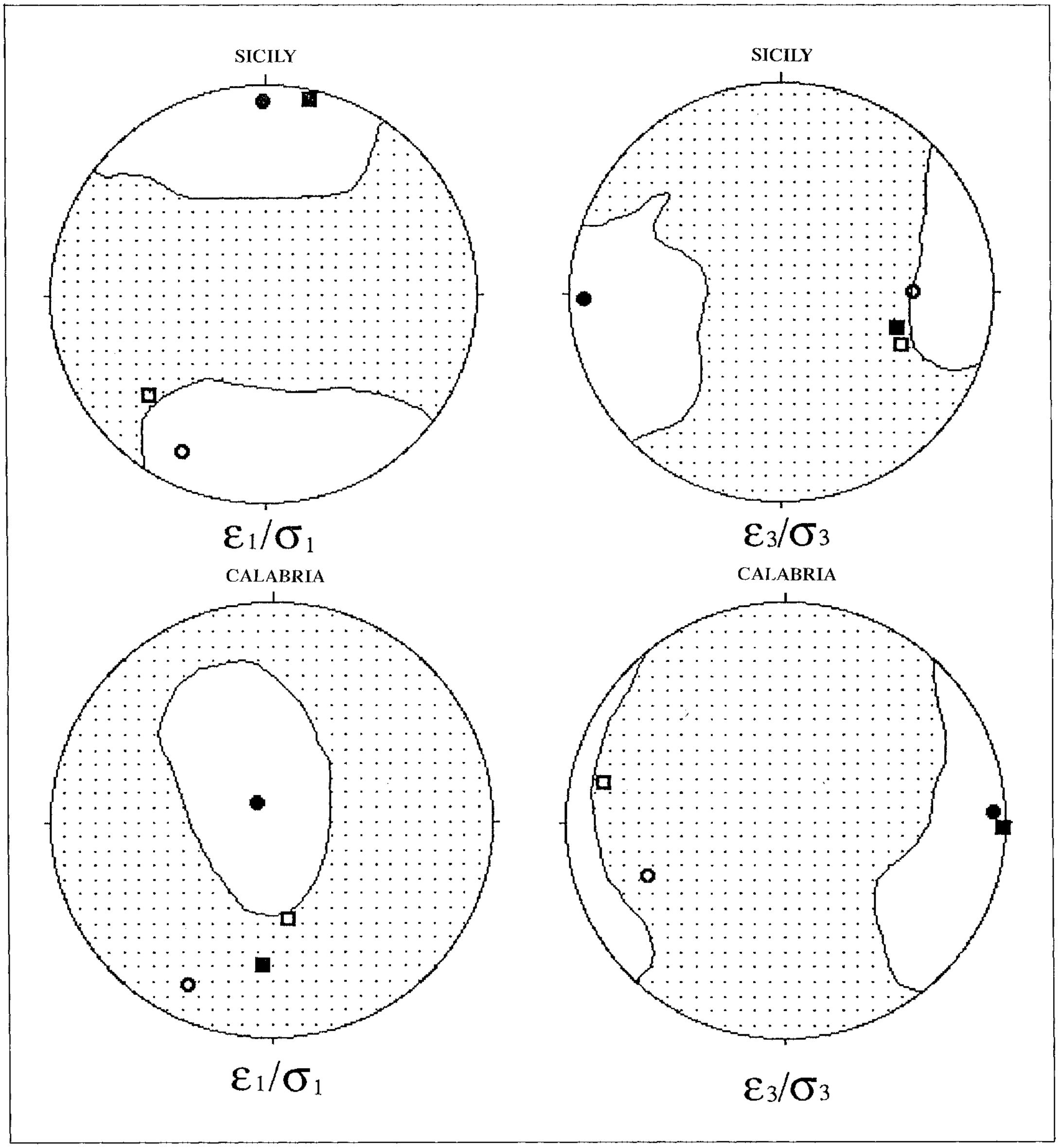

Fig. 3. Orientations of the principal strain and stress axes in Calabria and Sicily derived from the fault plane solutions shown in fig. 2. Black dots and white contoured areas respectively represent the poles of best fitting stress axis and the 90% confidence intervals obtained by the approach of Gephart and Forsyth (1984). Open dots are the poles of principal stress axes obtained by the right Dihedra approach (Carey-Gahilardis and Vergely, 1992). Open squares indicate the poles of principal strain axes obtained by the «Linked Bingham distribution analysis» (Marret and Allmendinger, 1990) and black squares are the principal strain axes obtained by Kostrov's (1974) approach. Lower hemisphere equal area projection; north is upward and east is towards the right.

above phenomenon is connected with an active rifting process. Other authors (Channell and Mareshal, 1988; Argnani, 1993) hypothesized that the troughs in the Sicily Channel opened up in response to a NEward drifting of Sicily, driven by «slab pull» mechanisms. Mantovani *et al.* (1996, 1997) argued that the above two hypotheses can hardly account for the time space distribution of compressional and extensional deformation events in the Central Mediterranean zone, with particular regard to the Tyrrhenian-Maghrebian system, the Calabrian arc and the Northern African margin, and for the kinematics of the confining major blocks, *i.e.*, Africa, Adriatic and Eurasia. The above authors suggested instead that the deformation pattern in Sicily and surrounding zones is mainly related to the convergence between Africa and Adriatic forelands which is assumed to occur along a SSW-NNE direction (Albarello *et al.*, 1993, 1995). The shortening required by this plate convergence is accommodated by lateral escapes of crustal wedges, whose relative motions with respect to the surrounding zones cause the observed pattern of compressional, tensional and transcurrent features. This work describes an attempt to quantify, by finite element calculations, the major consequences, in terms of strain and displacement fields, of the above geodynamic hypothesis. The results obtained by numerical experiments are then compared with observed features.

2. Modelling approach

A realistic modelling of tectonic processes in continental collision zones is a very difficult task, given the high complexity of crustal deformation processes which affect continental lithospheric structures characterized by rheological stratification and strong lateral heterogeneities (Meissner, 1986; Ranalli, 1987). However, some simplifications can be adopted if the analysis is limited to the study of short time intervals (hundreds of years), *i.e.*, those involved by seismogenic processes. In this case, deformations can be considered small everywhere, and thus the elastic approximation can be used to simulate the mechanical behaviour of shallow crustal bodies. In the area here considered, the reliability of this approximation is supported by the interpretation of gravimetric and structural data, which indicates the significant role played by the elastic flexural behaviour of the upper crust in the recent structural evolution at the scale length of tens of kilometres (Royden and Karner, 1984; Moretti and Royden, 1988; Cogan *et al.*, 1989; Albarello *et al.*, 1990; Barrier, 1992) comparable with lithospheric mechanic thicknesses deduced for the Mediterranean area by rheological models (Viti *et al.*, 1997).

Further simplifications can be introduced in the model if one assumes that tectonic processes are mostly related to horizontal tectonic forces, induced by the relative motions of major plates. The evidence and arguments which can support this hypothesis are reported by Mantovani *et al.* (1996, 1997). This assumption implies that a 2D plane stress approximation should not involve important deviations from reality in modelling the displacement and strain fields in the study area. A quite similar approach has been adopted by other authors (Kasapoglu and Toksoz, 1983; Shachinger, 1992; Grunthal and Stromeyer, 1992) to simulate the tectonic stress field in Central Europe and the Eastern Mediterranean.

Geological and geophysical evidence in the considered area suggests that an important role in the recent evolution has been played by major active margins and transform faults in accommodating the relative motions between relatively undeformed blocks (Finetti and Del Ben, 1986; Reuther *et al.*, 1993; Ben Avraham and Grasso, 1990). This hypothesis is also supported by some recent experimental results (Ratschbacher, 1991; Sornette *et al.*, 1993) and theoretical considerations which have stressed the importance of large faults in controlling tectonic processes (Thatcher, 1995; Twiss *et al.*, 1993).

On the basis of the above evidence and arguments, we approached the modelling by assuming that the system is constituted by poorly deformable blocks separated by major tectonic belts, where most deformation is accommodated. Poorly deformable blocks are simulated by isotropic elastic shells, convergent and divergent boundaries by isotropic elastic elements characterized by values of elastic parameters much lower (several orders of magnitude) than those of the surrounding «stable» areas. Transform faults are simulated by orthotropic elastic elements (Love, 1944; Lekhniskii, 1981) characterized by values of elastic parameters in the direction of the shear trend several orders of magnitude lower than those in the perpendicular direction. To obtain strain values of the order of magnitude of those actually observed in active faults (Sibson and Ramsay, 1982; Sibson, 1984; Smith and Bruhn, 1984; Williams and Richardson, 1991), the ratio between the values of the Young modulus parallel and perpendicular to the shear zone (E_x and E_y respectively) have to be of the order of 10^3-10^4. To avoid this high ratio producing unrealistic high strains in the direction of the fault, the Poisson coefficient in direction of the shear zones has to be very low.

To better understand this point, let us consider, for example, the simple case of a planar section of an orthotropic body characterized by $E_x \gg E_y$ and by Poisson coefficients ν_x and ν_y. This condition is supposed to simulate the behaviour of a transcurrent discontinuity with a shear oriented along the y axis. If this shear is loaded by a uniaxial compression along the x axis ($\sigma_{xx} \neq \sigma_{yy} = 0$), linear elasticity implies that:

$$\varepsilon_{yy} = -\nu_y \frac{E_x}{E_y} \varepsilon_{xx}.$$

If ν_y is significantly different from zero, the strain induced in the y direction (parallel to the shear) would become unrealistically high due to the large E_x/E_y ratio. In order to overcome this problem, a null value of ν_y has been assumed in the modelling of shear zones. Despite the fact that this choice is meaningless from the mechanical point of view and produces unrealistic stress/strain relations within shear zones, realistic strain and displacement fields can be obtained in this way. Due to these problems, the results of modelling will be considered significant only from the kinematic point of view.

3. Numerical procedure and model parametrization

Numerical modelling has been carried out by a finite element procedure in a plane stress approximation (Calladine, 1983). The numerical algorithm employs six-node isoparametric triangular shell elements with cubic basis functions. The resulting set of algebric equations has been solved by the Newton's method. Further details on the numerical technique are given by Sewell (1986).

Figure 4 shows the model finally adopted. The grid is constituted by 231 triangular plane shell elements whose sides connect 123 nodes. Given the relatively small dimension of the elements, earth curvature has been considered negligible.

The elastic behaviour of the shell elements in «stable» blocks is controlled by the isotropic Poisson coefficient and by the «conventional elastic modulus» given by the product between the Young modulus E and the elastic thickness h, which is representative of the mechanical lithospheric layer (Calladine, 1983). In the modelling here considered, we choose to assume for all stable blocks a unique value of the conventional elastic modulus ($2 \cdot 10^{15}$ Pa m) which corresponds to values of Young modulus and elastic thickness respectively equal to 10^{11} Pa and 20 km) and of Poisson modulus (0.25). In fact, since lateral variations of mechanical lithospheric thickness in the study area never exceed one order of magnitude (Viti *et al.*, 1997), one may reasonably expect that also the corresponding variations of short-term strain accumulation rates do not exceed one order of magnitude. Instead, strain accumulation rates in deformation belts are generally at least two orders of magnitude greater than those in the surrounding stable areas (Pfiffner and Ramsay, 1982; Lachenbruch and Sass, 1992; Bodri and Iizuka, 1993). Thus, it seems reasonable to assume that the effect of large tectonic discontinuities on the strain and displacements fields is much greater than the one induced by lateral variations in lithospheric thickness and thus that the last ones could be neglected in the numerical analysis. This conclusion is also supported by the results of some preliminary numerical computations.

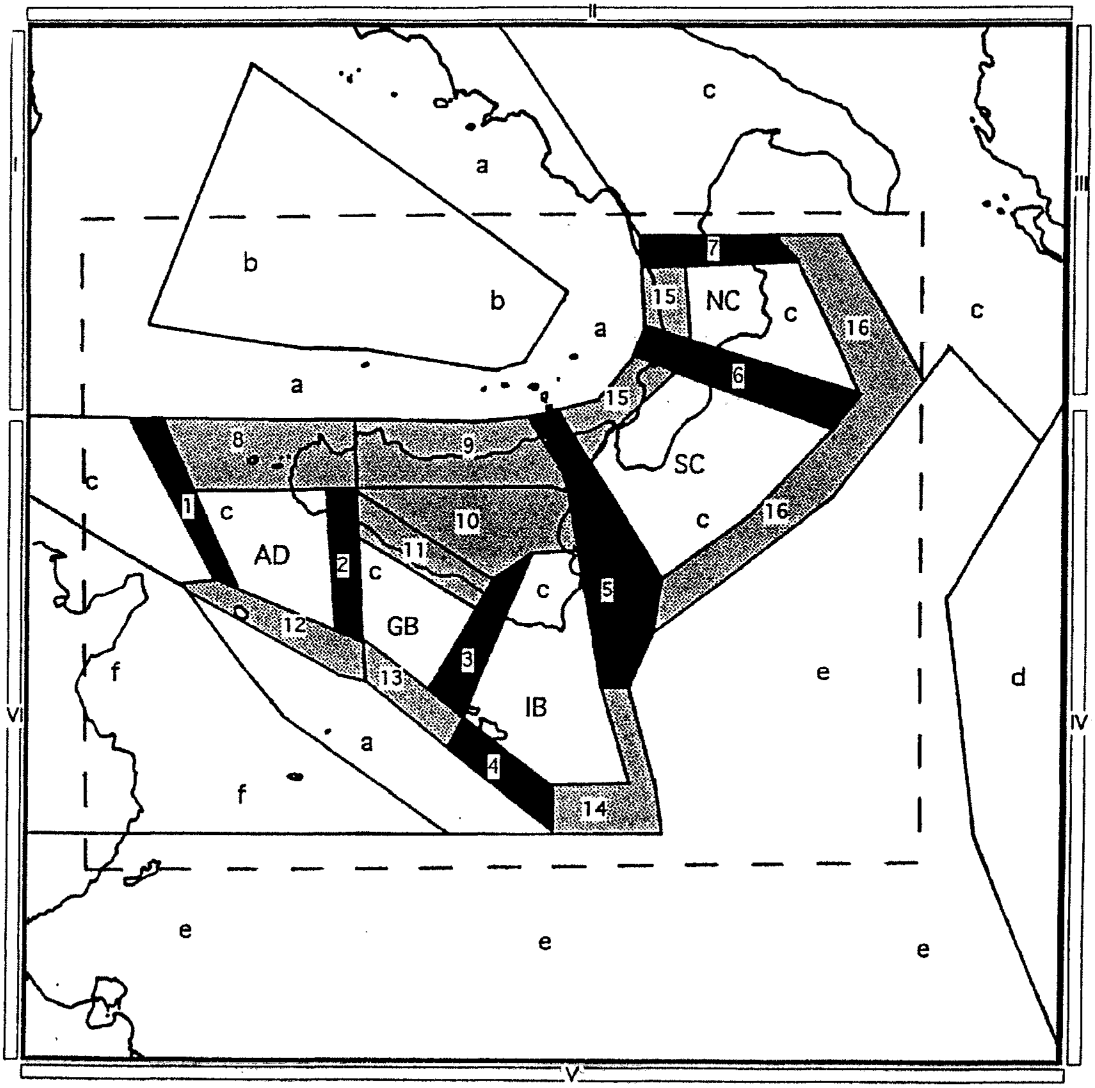

Fig. 4. Model adopted for finite element computations. Small letters identify «stable areas» (see text for explanation). Numbers identify the zones (tectonic discontinuities) where elastic parameters are considerably lower than those in the surrounding regions. Shear zones, where motions parallel to the fault are greatly privileged, are identified by black bands: 1) Egadi fault; 2) Sciacca fault; 3) Comiso-Scicli fault; 4) Malta fault; 5) Volcano fault; 6) Catanzaro fault; 7) Palinuro faults. Shaded bands try to simulate microplate borders, where underthrusting processes or tensional deformations take place. This kind of boundaries allow convergent and divergent motions between the adjacent blocks: 8) Adventure; 9) Northern Sicily; 10) Caltanissetta nappe; 11) Southern Sicily; 12) Pantelleria; 13) Linosa; 14) Medina; 15) Internal Calabria; 16) External Calabria. Roman numerals indicate the sectors of the borders where different kinematic boundary conditions have been applied (see text for details). Capital letters identify the crustal wedges cited in the text: AD = Adventure; GB = Gela; IB = Iblean; SC = Southern Calabria; NC = Northern Calabria. Dashed lines contour the zone which has been considered for the comparison between the results of numerical experiment and observations.

A tentative elastic parametrization of deformation belts has been carried out by a trial and error procedure, to obtain strain rates ranging between 10^{-13} and 10^{-15} s^{-1}, which can be considered realistic values for this kind of zones (Sibson and Ramsay, 1982; Sibson, 1984; Smith and Bruhn, 1984; Williams and Richardson, 1991).

The external boundaries of the mesh have been assumed to be far enough from the studied area (fig. 4) so that edge effects can be ignored.

We preferred to impose kinematic boundary conditions rather than boundary forces since we believe that the uncertainty on motion rates is much lower than that which may affect the estimate of tectonic forces, both concerning modulus and orientation. Along sectors I, II and III of the external border (fig. 4) only motions parallel to the boundary are allowed. These conditions try to simulate the present time very low mobility of the Adriatic and Corsica Sardinia block with respect to stable Eurasia (Mantovani *et al.*, 1996, 1997).

4. Main results

Figures 5 and 6 show the displacement and strain fields obtained by imposing a N20°E displacement of 1 m along sectors IV, V and VI of the external border (fig. 4). This displace-

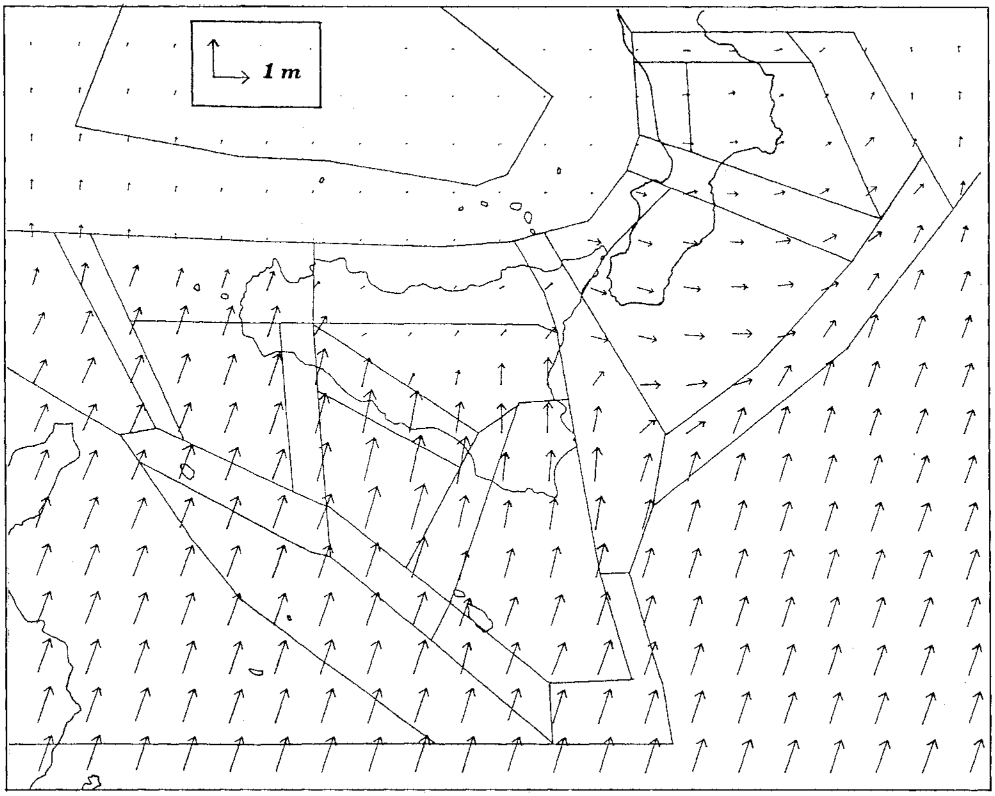

Fig. 5. Displacement field resulting from numerical modelling by imposing a 1 m displacement of Africa along a N20°E direction. The scale of displacements (arrows) is reported in the inset. Geographical contours and geometry of structural domains (fig. 4) are reported for reference. North is upward.

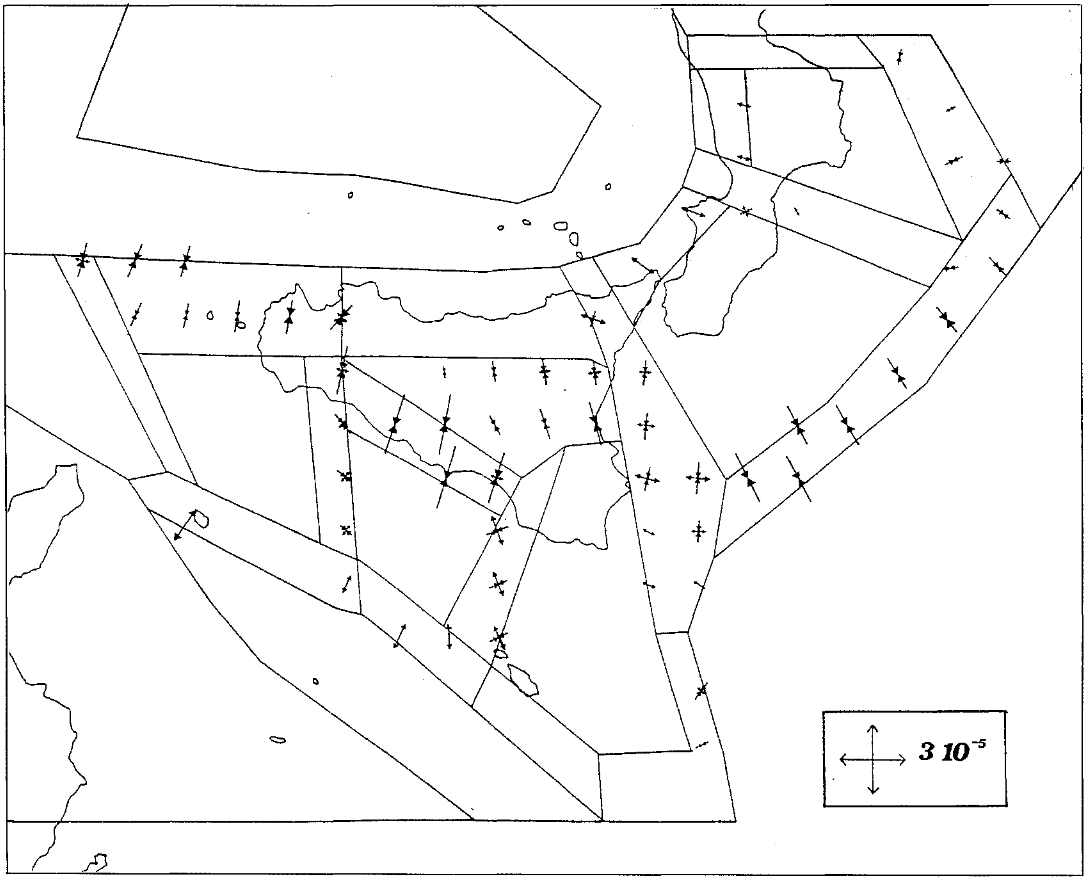

Fig. 6. Strain field associated to the displacements field shown in fig. 5. Principal strain directions are reported for a number of points representative of the local strain field. The length of arrows is proportional to local strain values, following the scale reported in the inset. Converging and diverging arrows respectively indicate ε_1 and ε_3 (maximum and minimum principal strain axis respectively) directions. Geographical contours and geometry of structural domains are reported for reference. North is upward.

ment roughly corresponds to the drifting of Africa during a time span of 150 years, in accord with the kinematic pattern proposed by Mantovani *et al.* (1993, 1996) and Albarello *et al.* (1993, 1995).

It can be noted that boundary conditions are accommodated by the lateral escapes of crustal wedges in the zone of maximum compression. The Calabrian wedges extrude roughly eastwards. This motion is allowed by the shortening of the «weak» boundary with the Ionian zone, which simulates the consumption of thinned Ionian lithosphere beneath the Calabrian arc (Rossi and Sartori, 1981; Finetti and Del Ben, 1986; Bousquet and Philip, 1986).

In the wake of the Calabrian blocks, extension occurs at the boundary with the Tyrrhenian area (see fig. 6). The extensional rate in this zone, about 2.0 mm/yr (≈30 cm in 150 years, fig. 5), is compatible with the Quaternary extensional rate observed in Southern Calabria (Westaway, 1993), with the strain rates deduced by geodetic measurements (Baldi *et al.*, 1983) and with the results of the moment tensor analysis carried out in this work (see table I). The transcurrent motions resulting along the lateral guides of Calabria, characterized by sinistral shear along the Palinuro fault and dextral shear along the Vulcano fault (see fig. 5), agree with neotectonic observations (Finetti and Del Ben, 1986; Van Dijk and Okkes, 1991).

The southern part of the Iblean microplate tends to move roughly NNE, parallel to the African displacement, while in the northern part this block moves roughly northward. This deviation is most probably due to a series of factors, such as the low compressibility of the Calabrian wedge, the presence of the Volcano transform fault and the «soft» border lying north of the Iblean block. The kinematics of the Iblean zone shown in fig. 5 is consistent with the results of the first VLBI measurements in the station of Noto, located in the southernmost edge of Sicily (Zarraoa *et al.*, 1994; Lanotte *et al.*, 1995).

The displacement of the Iblean block creates compressional stresses in the Gela crustal wedge, which, consequently, tends to escape roughly NNE. This escape is accommodated by shortening of the «soft» boundary in Central Sicily (Caltanissetta nappe), which simulates the underthrusting process occurring at this border.

In the wake of the Gela block, extensional strains occur along the boundary with the African foreland, so reproducing the extensional tectonics observed in the Sicily Channel. The extensional rate resulting from modelling in this zone (≈ 1-2 mm/yr) is compatible with the indications of neotectonic data (see, *e.g.*, Reuther *et al.*, 1993).

The sinistral and dextral shear resulting in the Sciacca and Comiso-Scicli faults respectively agree with the direction of transcurrent motion observed in these zones (Argnani *et al.*, 1987; Finetti and Del Ben, 1986; Reuther, 1993; Ben Avraham and Grasso, 1990). In fig. 6 it is possible to note that, apart from the Sicily Channel and the Ionian border of Calabria, the whole region is affected by a strain field characterized by a SN to SSW-NNE compression and a E-W to WNW-ESE extension, which is in good agreement with the seismotectonic information described earlier.

5. Discussion

The displacement and strain fields shown in figs. 5 and 6 are the final results of a series of numerical experiments we carried out by changing a number of model parameters concerning boundary conditions and discontinuities in order to best fit observations. Thus, the good experimental-theoretical fit finally obtained cannot be used as a demonstration of the fact that the adopted tectonic interpretation is better than the others previously proposed. The usefulness of the results obtained is that they prove that the deformation pattern in the Central Mediterranean area may be explained as an effect of horizontal forces induced by the «Africa-Adriatic» convergence without invoking «local» driving forces, such as, *e.g.*, those connected with «slab pull» or «active rifting» mechanisms.

The reliability of the results obtained might be undermined by the fact that the adopted modelling approach involves some simplifications with respect to the real behaviour of the Earth. The first important limitation concerns the use of elastic elements. This choice would be scarcely reliable if one tried to model long-term tectonic processes. However, the very short time interval here used implies that the strain is quite small (of the order of 10^{-5}). Thus, the difference between the real kinematic field (out of deformation belts) and the one we obtained can reasonably be considered negligible.

Another simplification of the model is given by the «plane stress» approximation. The reliability of this choice depends on whether the model can be considered very thin with respect to its lateral extension. In our case, this condition seems to be fulfilled given the small thickness of elastic blocks (≈ 20 km) with respect to their average horizontal dimensions (of the order of ≈ 100 km). This hypothesis implies that the mechanical contribution of the resistant mantle layer to the total lithospheric strength is negligible in the study area. This seems the case in most of the zones considered (Viti *et al.*, 1997). Furthermore, as suggested by Grunthal and Stromeyer (1992), this assumption could be justified by the ductile behaviour of the lower crust in the zones considered (Viti *et al.*, 1997), which may allow the decoupling of the upper crustal layer from the underlying lithospheric mantle.

The third major simplification of the model concerns the fact that deformation belts have been simulated by using elastic elements. One must be aware that this simplification does not simulate the complex tectonic processes which take place in this kind of zones. However, it seems reasonable to assume that, when short time intervals are considered, average forces resisting deformations at the boundaries of the belts, being the resultant of all forces (friction on major faults, buoyancy and viscous resistence to subduction, etc.) which actually exist within the belt, linearly depend on the average deformation of the whole tectonic structure. On this assumption, the use of elastic elements (isotropic or orthotropic) to simulate short-term tectonics may represent a first order approximation of the average mechanical behaviour of true deformation belts. In this context, numerical values of elastic constants used to characterize these structures (table II) should only be considered numerical artifacts useful to reproduce realistic strain rates.

Different modelling approaches in terms of viscous/viscoelastic deformation of lithospheric sheets subjected to horizontal tectonic loads and buoyancy forces have been proposed by other authors (England and McKenzie, 1982; England and Houseman, 1989). More recently, Bird (1989) proposed a more sophisticated version of this kind of approach by assuming a rheological stratification of the tectonosphere, which includes the elastic-brittle behaviour of the shallow crust. This approach has been used by Bassi and Sabadini (1994) to model the Central Mediterranean deformation pattern. This kind of modelling could neglect a basic aspect of the real tectonic processes, *i.e.*, the presence of major discontinuities where most deformation is accommodated. The basic role played by tectonic discontinuities (in both shallow brittle structures and deeper parts of the lithosphere) in geodynamic processes has been stressed by several authors, on the basis of observational evidence and mechanical experiments (Tapponier and Molnar, 1976; McKenzie and Jackson, 1983, 1986; Kirby, 1985; Scotti and Nur, 1990; Ratschbacher *et al.*, 1991; Jackson, 1993; Twiss *et al.*, 1993; Sornette *et al.*, 1993; Avouac and Tapponier, 1993; Vissers *et al.*, 1995; Thatcher, 1995). The importance of this problem in the area here considered is underlined by a large amount of geophysical-geological data, as mentioned earlier in this work.

Table II. Elastic parameters of weak zones (indicated by numbers in fig. 4) corresponding to interplate boundaries. For transform boundaries, the values of Young modulus parallel (E_y) and perpendicular (E_x) to the shear zone are reported. The azimuth of the shear zone is indicated by θ.

Zone	E_x (10^{10} Pa)	E_y (10^{10} Pa)	θ (°)
1	10	0.01	−23
2	1	0.01	−10
3	10	0.01	19
4	10	0.01	−51
5	10	0.01	−33
6	10	0.01	−70
7	10	0.01	90
8,10,16	0.01	0.01	*
9	0.1	0.1	*
11,15	0.001	0.001	*
12,13,14	0.001	0.001	*

6. Conclusions

It has been tentatively shown by finite element computations that the main features of the observed displacement and strain fields in the Calabrian arc and surrounding regions can be satisfactorily reproduced as effects of horizontal forces induced by the convergence of the major confining blocks *i.e.*, Africa, Adriatic and Eurasia. The proposed modelling approach tries to simulate the presence of major tectonic discontinuities – indicated by seismotectonic studies – by the use of highly deformable narrow zones.

The kinematic boundary conditions imposed on the model are accommodated by the lateral escape of crustal wedges in Calabria and Sicily. The resulting microplate kinematics produces the distribution of recent-present compressional, tensional and transcurrent deformations observed in the study area. This could imply that «internal» driving forces, such as gravitational sinking or active rifting, are not necessary to account for extensional tectonics in the Southern Tyrrhenian and Sicily Channel.

The results obtained point out that the presence of major tectonic discontinuities where strain can be much higher than in the surrounding zones strongly affect the computed displacement field. This implies that modelling approaches which neglect such tectonic features could provide unreliable indications.

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