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Contribution of structural analysis to understanding the geodynamic evolution of the Calabrian arc (Southern Italy)

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Abstract—A marked curvature of crustal structures characterizes the Calabrian arc in Southern Italy. The overall deformation of the arc seems mostly controlled by the Sangineto shear zone to the north and by the Mt. Kumeta–Alcantara shear zone to the south, which both separate different crustal sectors. Other important fault systems cut the Iblean foreland (Scicli–Ragusa fault zone) and many others dissect the crystalline units of Central Calabria. Neotectonic structural analyses have been carried out in order to recognize the character of the Plio–Pleistocene tectonic phases and their bearing on the present configuration of the arc.

After the Middle Miocene extensional phase an Early–Middle Pliocene compressional phase is detectable in many parts of the arc. Right- and left-lateral displacements respectively characterize the Mt. Kumeta–Alcantara and Sangineto shear zones and right-lateral movements are also detectable within the Scicli–Ragusa fault system.

Finally, the Pleistocene tensional regime seems to have been controlled mainly by uplift. The structural and neotectonic data allow us to propose a model of the recent evolution of the arc, which was bent mainly as a result of opposed wrench faulting along the Sangineto and Mt. Kumeta–Alcantara shear zones.

INTRODUCTION

THE PROMINENT bending of crustal structures in Southern Italy is associated with the so-called Calabrian arc (Fig. 1) which is made up of allochthonous crystalline units, of Alpine provenance, emplaced onto Apenninic thrust sheets. Its general arcuate trend, extending from the Lucania–Calabria boundary to the Northern range of Sicily, is also reflected by changes in strike of the fault systems in the area. The faults show a N–S trend in Northern Calabria, a NE–SW trend in Southern Calabria and an E–W trend in Northern Sicily (Fig. 1). Sharp points of bending mostly occur where other fault systems of transverse orientation intersect the arc and their trends also seem to be consistent with a general rotation of the structures from an E–W direction in Northern Calabria to a NE–SW direction in Sicily. It therefore appears that the overall deformation of the arc has been achieved by composite shearing on fault systems which determine both the disruption of the entire structure and the relative displacements of the blocks along the fault boundaries.

Any tectonic interpretation of the Calabrian arc cannot ignore the age of the faults, the mutual relationships between longitudinal and transverse systems, the sequence and character of movements on the fault planes, and the response of different sectors of the arc to subsequent tectonic phases. Their analysis, which can be investigated by microtectonic methods, must necessarily consider the influence of the dynamics of the arc on the Plio–Quaternary sedimentary evolution of different crustal zones, in order to verify if the deformation of the Calabrian arc has been a neotectonic event (Ghisetti & Vezzani 1979a), which still controls the intense seismicity and volcanic activity of the area (Barbano *et al.* 1978, Cristofolini *et al.* 1977).

STRUCTURAL SETTING OF THE CALABRIAN ARC

The most important shear zones which appear to play a fundamental role in the overall deformation of the Calabrian arc, are the Sangineto line along the Northern Calabrian boundary and the Mt. Kumeta–Alcantara line along the southern margin of the Sicily range (Fig. 1). The two shear zones separate crustal sectors of different structural characteristics. The Sangineto line is an ancient structural boundary which delimits to the south the Alpine crystalline units of Calabria from the calcareous thrust sheets of the deformed African margin to the north. An identical tectonic role is played in Sicily by the Taormina line (Amodio-Morelli *et al.* 1976), which bounds to the south the crystalline units of the Peloritani range, but which does not show any sign of recent activity, in contrast to the Sangineto line.

The Mt. Kumeta–Alcantara line truncates to the south the thrust sheets of the Northern Sicily coastal range, uplifted in Late Pliocene–Pleistocene times, and probably overriding the Neogene terrigenous sequences of the Caltanissetta basin. The line was active until Late Pleistocene times, thus determining the relative motion and the different evolution of the two crustal blocks of the coastal range and the Caltanissetta basin.

A third system of faults separates the Apenninic thrust belt from the Iblean and Apulian zones. These parts of the Africa foreland are connected, externally to the arc, through the Ionian basin, as inferred by many authors (e.g. Amodio-Morelli *et al.* 1976). The foreland margin gradually declines towards the internal zones under the Apenninic thrust sheets, as a consequence of step-like systems of normal faults, trending NW–SE in Apulia and NNE–SSW and E–W in the Iblean region. The stable

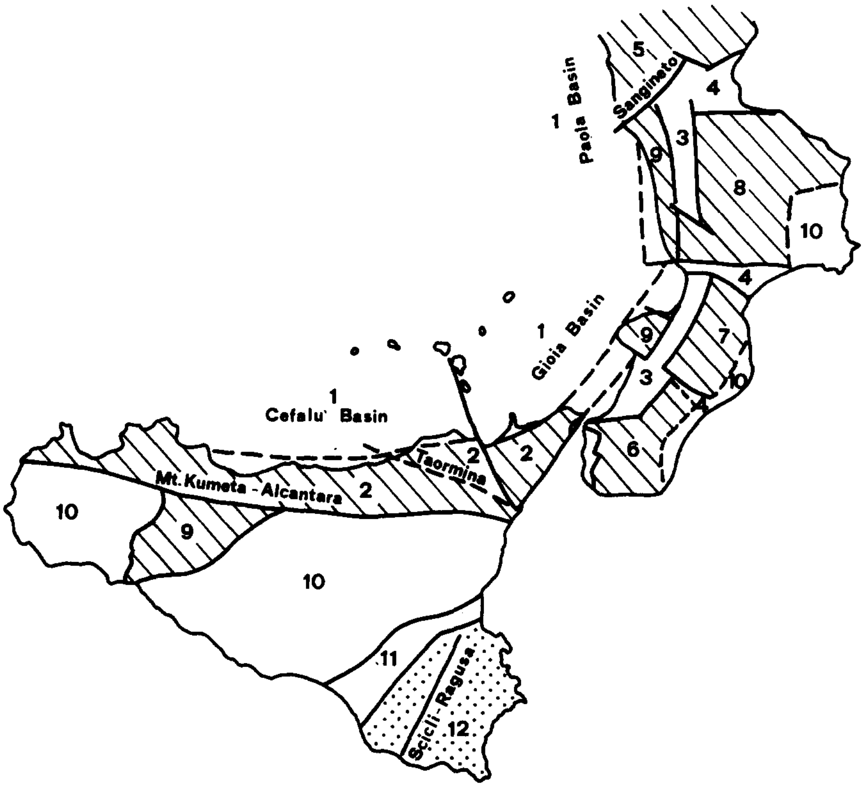

Fig. 1. Principal neotectonic blocks within the Calabrian arc. 1, Peri-Tyrrhenian basins; 2, Palermo, Madonie, Nebrodi and Peloritani Mountains; 3, Mésima and Upper Crati basins; 4, Lower Crati, Catanzaro and Siderno basins; 5, Southern Apennines chain; 6, Aspromonte; 7, Serre; 8, Sila; 9, Cape Vaticano, Coastal Chain; 10, Crotone–Spartivento, Caltanissetta and Castelvetrano basins; 11, Gela–Catania trough; 12, Iblean plateau. Hatched areas, orogenic belt; white areas, post-orogenic basins; dotted area, foreland.

foreland also seems to have experienced a complex tectonic history after the Middle Miocene (Ghisetti & Vezzani 1980).

As previously mentioned, many other important fault systems intersect the Calabrian arc determining its tectonic dissection (Fig. 1) and controlling the contrasting neotectonic evolution of the range and basin zones (Ghisetti & Vezzani 1979b). These systems act as major discontinuities within the arc, but they are confined between the Sangineto and the Mt. Kumeta–Alcantara faults so that their activity seems to have been mostly controlled by displacements along the two main shear zones.

FAULT ACTIVITY IN RELATION TO TECTONIC PHASES

It is difficult to date the initiation of most of the fault systems within the arc (Figs. 2 and 3). While some faults are almost certainly inherited from more ancient structures (e.g. the Sangineto and Taormina lines), others appear to be connected with more recent tectonic phases.

Neotectonic analyses (Ghisetti & Vezzani 1979b) have shown that the most important faults began to be active (or were reactivated) from at least Middle Miocene times onwards, even if they are characterized by different mechanisms during subsequent tectonic phases. Three such subsequent phases are recognizable (Selli 1974, Ghisetti 1979a): a Tortonian–Messinian extensional phase, an Early–Middle Pliocene compressional phase, and a further extensional phase dated as Late Pliocene–Pleistocene.

The analytical data supporting the recognition of the phases derive from both detailed regional mapping and stratigraphical studies, as well as from structural and microtectonic investigations (Atzori *et al.* 1978, Ghisetti 1979a, Ghisetti & Vezzani 1980).

Tortonian–Messinian extensional phase

The opening of post-orogenic basins occurred during the Middle–Late Miocene immediately after the final emplacement of nappes in Sicily and Calabria. The development of the most important troughs (Upper and Lower Crati, Mésima, Catanzaro, Siderno,

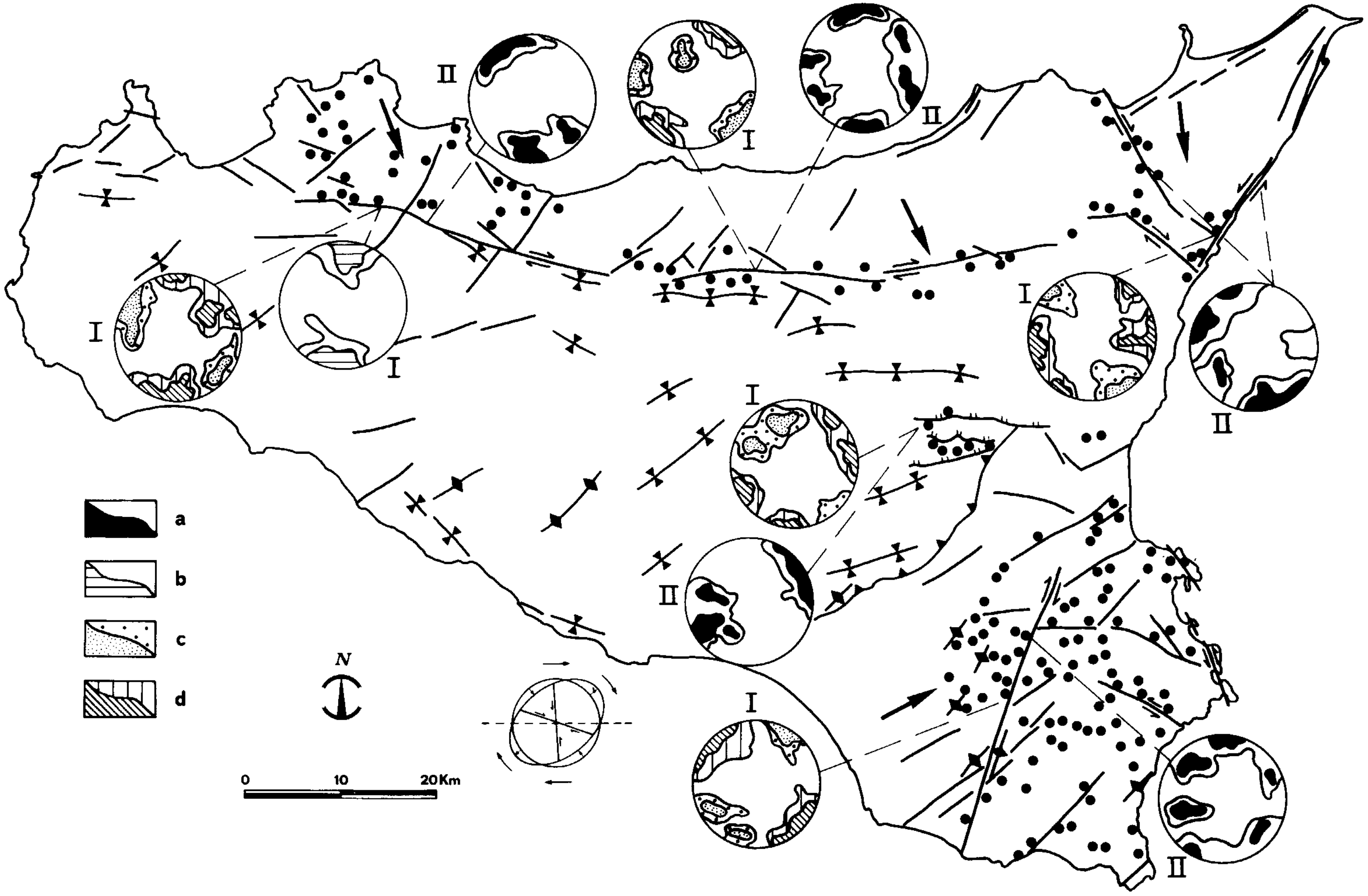

Fig. 2. Principal structures of Sicily; dots represent microtectonic sampling sites. a, normal faults; b, reverse faults; c, left-lateral faults; d, right-lateral faults (Schmidt lower-hemisphere plots, contour interval 10% per 1% area); I, Early–Middle Pliocene compressional phase; II, Late Pliocene–Pleistocene extensional phase. A strain ellipse for an E–W shear couple is shown.

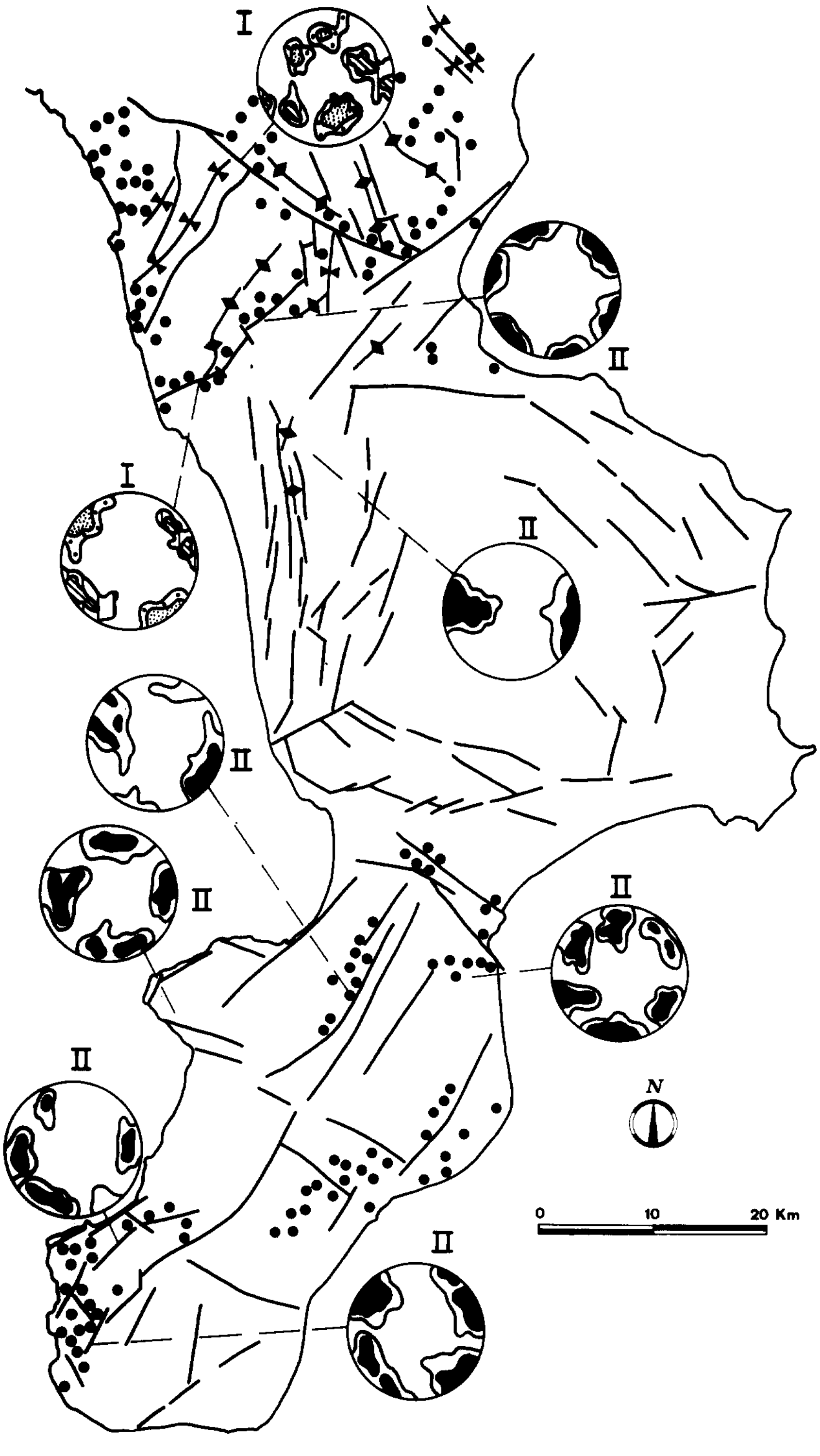

Fig. 3. Principal structures of Calabria; symbols as in Fig. 2.

Crotonè–Spartivento, Reggio Calabria, Caltanissetta, Castervetrano) occurred during Tortonian times, as proved by the transgressive character of Tortonian basal sequences (conglomerates, sandstones and clays) over the thrust sheets. Most of the basins are bounded by normal faults of regional extent, delimiting subsided and uplifted zones (e.g. the Coastal Chain, Sila, Cape Vaticano, Serre and Aspromonte blocks in Calabria and the Peloritani, Nebrodi, Madonie and Sicani blocks in Sicily).

It is difficult from microtectonic analyses alone to separate the Tortonian–Messinian activity from later activity. Tension joints and normal faults are characteristic structures in the Tortonian and Messinian sediments, but slickensided surfaces commonly show different generations of striae superposed on each other, some of which indicate opposite directions of movement. It is therefore more reasonable to consider only the regional evidence for the tensional character of this phase, which is well displayed in the Tyrrhenian and Ionian zones (Selli 1974, 1975, Fabbri *et al.* in press, Rossi & Sartori in press).

Early–Middle Pliocene compressional phase

In many sectors of the Calabrian arc this phase is recognizable on both a regional and microtectonic scale.

Northern Sicily–Mt. Judica–Catania plain. In this part of the arc right-lateral shear associated with the Mt. Kumeta–Alcantara line has been demonstrated (Ghisetti 1979a), (Figs. 1 and 2). In the Caltanissetta basin, immediately to the south of the Mt. Kumeta–Alcantara line, the Upper Miocene–Lower Pliocene sequences are intensively deformed by a right-lateral en échelon fold system, mainly directed NE–SW (Fig. 2), but assuming an E–W direction near the fault trace. E–W fold axes can be detected again at the southern margin of the basin, so that a Z-shaped pattern is formed by the fold systems. Because these folds affect only Tortonian–Lower Pliocene sequences and are unconformably overlain by Upper Pliocene–Pleistocene sediments, the age of the deformation can be dated precisely. Probably of the same age is a continuous belt of high-angle E–W reverse faults. The Mt. Kumeta, Rocca Busambra, Mt. dei Cervi, Mt. Sambughetti, Mt. Zimmara and Mt. Judica structures are interpreted as upthrust blocks detached from their substratum during Early–Middle Pliocene wrench faulting along the E–W Mt. Kumeta–Alcantara line.

A well-developed system of synthetic faults (Fig. 2), intersecting the Mt. Kumeta–Alcantara line at a small angle, is represented by abundant NNW–SSE and NW–SE faults which cut the northern chain of Sicily. Along some of them (e.g. the Tindari–Letojanni and Alcantara fault systems) right-lateral displacements of about 7 km can be ascertained by regional offsets (Atzori *et al.* 1978, Ghisetti 1979a). In addition, a third system of mainly NE–SW trending faults probably represents the anthithetic conjugate direction (Fig. 2). Based on a regional analysis, left-lateral shear has been postulated for the NE–SW Messina–Giardini fault (Ogniben 1969), an interpretation opposed by some authors (e.g. D'Amico *et al.* 1973, Mascle 1974).

Detailed microtectonic analyses (Fig. 2) confirm that along E–W, WNW–ESE and NW–SE faults there was right-lateral shear and that along NE–SW faults there was left-lateral shear. Near upthrust bodies, reverse displacements on E–W planes prevailed (Fig. 2). NE–SW and E–W axes of small-scale folds are also present.

The above data seem therefore to be consistent with E–W right-lateral shear along the Mt. Kumeta–Alcantara wrench, in response to a stress field in which σ_1 was oriented NW–SE, a direction of maximum compression also given by horizontal stylolitic columns of tectonic origin.

South-eastern Sicily (Iblean region). The Iblean foreland has always been considered to be an area which experienced an independent tectonic history. In particular, earlier authors (e.g. Ogniben 1969) emphasized its stability, its weakly deformed character and the abundance of normal faults reflecting a tensional regime. This model does not reflect a complex history of movements associated with the main fault systems (Fig. 2), as shown by the microtectonic data collected by Ghisetti & Vezzani (1980).

Despite the evidence for normal faults being dominant on a regional scale (e.g. the grabens of Scordia–Lentini and Floridia), there is clear evidence for wrench faulting along all the main fault systems whose striated planes commonly show that different displacements have been superposed. The Scicli–Ragusa fault system, which crosses the plateau in a NNE–SSW direction, shows signs of there having been associated right-lateral slip, a displacement sense confirmed by the right-lateral character of NE–SW trending synthetic faults (e.g. the Comiso–Chiaramonte fault zone), which intersect the Scicli–Ragusa fault system at a small angle. Associated with this important wrench-fault phase there are gentle folds trending NE–SW. In the area of Licodia Eubea and along the Ionian margin of the Iblean region, folds of this trend affect the Lower Pliocene sequence, thus allowing their Early Pliocene age to be demonstrated. The persistence of wrench faulting until this time is also demonstrated by the presence of strike–slip striations on fault planes in Lower–Middle Pliocene volcanites. It is important to point out that the Scicli–Ragusa fault system intersects the principal volcanic centres of the Iblean region, which were mainly active in Miocene times.

Associated with the right-lateral Scicli–Ragusa fault system are left-lateral anthithetic conjugate faults mainly trending NNW–SSE and developed principally in the Vizzini, Siracusa and Canicattini areas (the Mt. Tauro–Siracusa fault system). The same interpretation can also be made for the important fault system which to the east truncates the Iblean platform from the Ionian bathyal plain, and which probably extends in a NW–SE direction to the Maltese islands (Patacca *et al.* 1979, Illies 1979). E–W faults in the Vizzini–Siracusa fault system show either right- or left-lateral displacements.

As pointed out previously, even if it seems that during Early–Middle Pliocene time there was an important compressional phase, on a regional scale tectonic troughs induced by tension were widely developed. Most of them can be reconciled easily with the Late Miocene tectonic phase, but they were also actively subsiding in Pliocene times, if the age of sediments which fill the grabens is considered (Grasso *et al.* 1979, Ghisetti & Vezzani 1980). It is however interesting to note that two of the most important grabens within the area (the Catania trough to the north and the Pantelleria rift to the south) are orientated with respect to the right-lateral Scicli–Ragusa fault zone such that, according to a model put forward by Tapponnier & Varet (1974), their opening can be reconciled (Ghisetti & Vezzani 1980) with the wrench fault phase. Therefore different structures can be attributed to the Early–Middle Pliocene phase in the Iblean area. Considering the relationships between the displacements on the faults and their geometry, as well as the orientations of the folds and horizontal stylolitic columns, it is possible to infer that the σ_1 axis was mainly oriented E–W. This conclusion is the opposite to that which has been inferred for the Northern Sicily chain, despite the structures being of the same age.

Southern and Central Calabria. In this part of the arc, which extends from the Messina Strait to the Catanzaro graben (Figs. 1 and 3), the effects of any important compressional tectonics seem to be lacking. The fault systems of the area, which are mainly oriented NE–SW, NW–SE and E–W (Fig. 3), delimit important grabens, bounded by normal faults on both a regional and microtectonic scale. Evidence for wrench faulting is rare and only found in pre-Pliocene terrains (Fig. 3). Again they indicate left-lateral displacements along NE–SW faults and right-lateral displacements along NW–SE faults. On E–W faults evidence for both right- and left-lateral slip has been found. The above pattern is well-expressed in the Reggio Calabria area but it is less uniform in the Cape Vaticano, Mésima and Serre zones where the majority of faults are normal irrespective of their orientation. Evidence for strike–slip displacements is lacking in this area, except for some rare observations on fault planes which affect the crystalline terrains.

Only in the external part of this region, along the Ionian margin of Calabria (Crotone–Spartivento basin and external Calabrian arc), are there well-developed fold systems and reverse faults of NE–SW trend (Selli 1975, Rossi & Sartori in press) which indicate a compressional regime. Because these structures affect Lower Pliocene sequences (Burton 1971, Rossi & Sartori in press), this phase appears to be contemporaneous with, but of a different character to, those elsewhere detected in the arc, and may be related to a stress field in which the σ_1 axis was orientated WNW–ESE.

Calabria–Lucania boundary. Along the northern margin of Calabria the ENE–WSW trending Sangineto line seems to have represented an important transcurrent boundary during the Early–Middle Pliocene compressive tectonic phase. Its left-lateral character has often been used to explain the present position of the Calabrian crystalline massif detached from the Tyrrhenian domain (e.g. Amodio-Morelli *et al.* 1976), but until the present no data have been presented about its deformational history.

Neotectonic and microtectonic analyses were carried out in this region to ascertain the character of the movements on this line during the Early–Middle Pliocene. The data collected indicate that activity on the Sangineto line and along the conjugate direction (the Pollino line) in Pliocene times was dominantly of strike–slip type, horizontal striations on faults being especially abundant. The movements detected on the fault planes indicate the overall left-lateral character for the Sangineto line and the right-lateral character of the Pollino line.

Along the northeastern margin of the Plio-Pleistocene San Arcangelo basin, located to the north of the Sangineto shear zone, there are WNW–ESE and NW–SE folds, thrusts, and also piercement slices (Craco, Cozzo Iazzicelli), which could be other structures associated with the shear zone. They deform Lower Pliocene sediments, and hence there is also evidence for Early–Middle Pliocene compression in this region.

Late Pliocene–Pleistocene extensional phase

All the most important faults of Calabria and Sicily were reactivated with normal displacements during the Late Pliocene–Pleistocene tectonic phase. The Plio–Pleistocene marine sediments which fill the Crati, Mésima, Reggio Calabria, Catanzaro, Siderno, Caltanissetta and Catania–Gela troughs, the Middle–Upper Pleistocene continental terraces, and the Eolian and Etna volcanites have been displaced by normal faults. The throws reach tens of metres (Ghisetti & Vezzani 1979b). The recent activity on the most important faults is reflected by their close control on surface morphology (see e.g. Ghisetti & Vezzani 1978, Ghisetti *et al.* 1979, Ghisetti 1980).

The microtectonic data (Figs. 2 and 3) collected in different regions of the arc confirm this interpretation; they clearly indicate normal movements along NE–SW, NW–SE and E–W striking faults affecting the Upper Pliocene–Pleistocene sediments and volcanites. The renewed activity on the older fault planes is reflected in places by dip–slip striations being superimposed on strike–slip slickensided surfaces.

A mechanism which could explain the observed kinematics, links the development and reactivation of these faults to Late Pliocene–Pleistocene uplift. Uplifting rates, as inferred from the height of a Lower Pliocene surface (Ghisetti & Vezzani 1979b) and the heights of Pleistocene continental terraces in Southern Calabria (Ghisetti 1980), indicate that uplift velocities markedly increased after 1.5 Ma. Different blocks in Southern Calabria are moreover characterized by differential uplift rates which were greater in the Cape Vaticano, Serre and Aspromonte blocks compared with the adjoining Mésima, Catanzaro and Reggio Calabria troughs. On this regional tendency, which is well expressed in many parts of the arc (Kieffer 1972), is superposed the fault activity, which emphasizes the differential uplift.

Although the general tensional character of the Late Pliocene–Pleistocene tectonic phase is clear, there is evidence in some areas for a compressional regime which migrated with time towards the more external areas, and which is connected with the Pleistocene emplacement of the Metaponto and Gela nappes (Ogniben 1969, Di Geronimo *et al.* 1978, 1979). The structures connected with these nappes (folds, reverse faults, thrusts) are mostly epidermic.

A DEFORMATIONAL MODEL FOR THE CALABRIAN ARC

The three main tectonic phases which have affected the Calabrian arc since Tortonian times have largely determined the present organization of the structural elements within the region.

Any model must consider the original structural trend of the Calabrian–Sicilian domain immediately after the climax of the Alpine orogeny and the contemporaneous opening, in Tortonian times, of both the longitudinal and transverse grabens (Fig. 4). Although the longitudinal troughs of Crati, Mésima and Caltanissetta follow the general curvature of the arc, the transverse troughs of

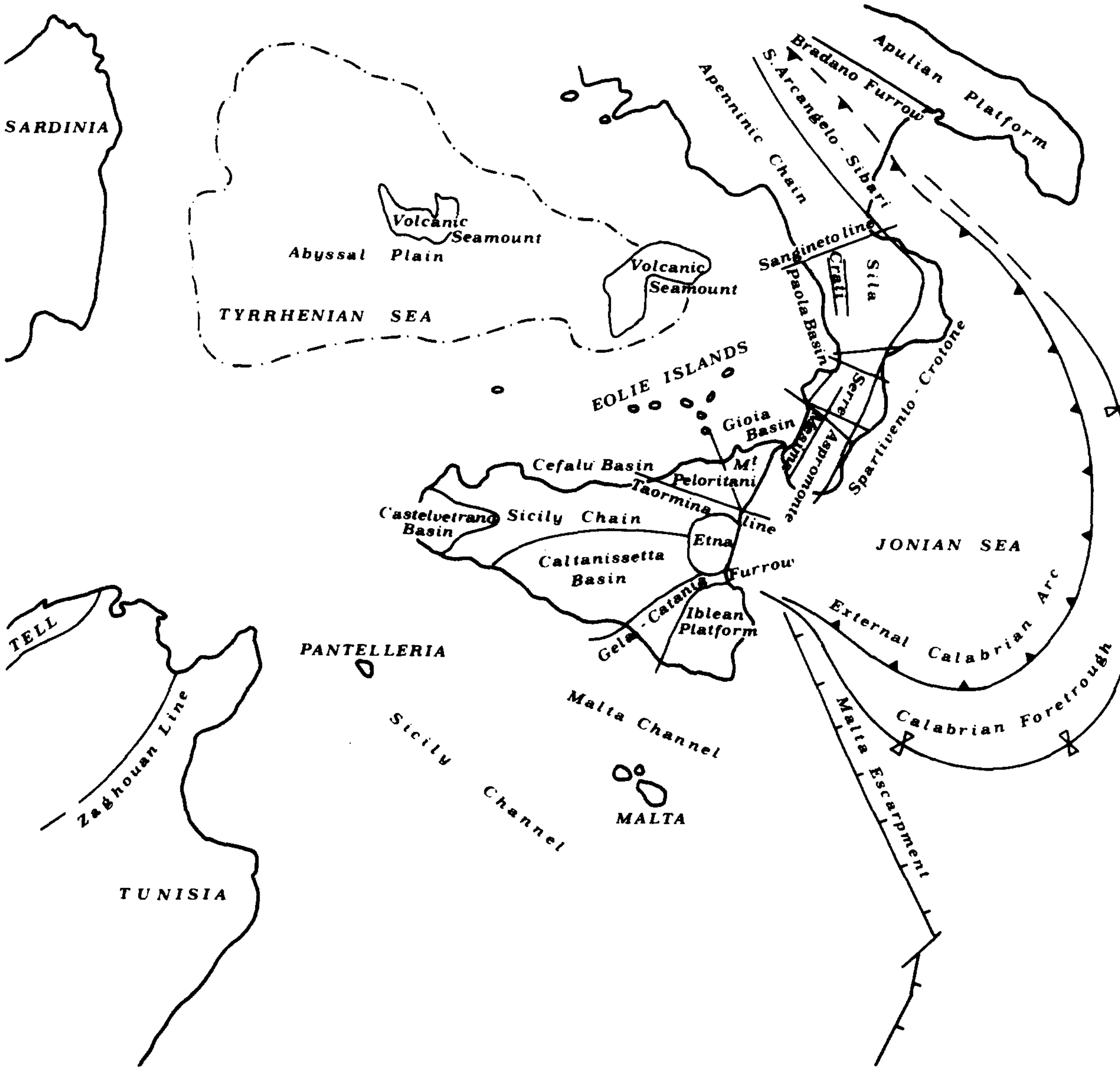

Fig. 4. Schematic representation of the principal structures of the Calabrian arc. The area between the Sangineto and the Taormina lines corresponds to the domain of the Calabria–Peloritani crystalline rocks.

Sibari, Catanzaro, Siderno and Reggio Calabria open in a fan-like form towards the Ionian sea, and disrupt the main structural trend where it changes direction. Thus the overall curvature is determined by a discontinuous deformation largely controlled by the transverse grabens.

During the Early–Middle Pliocene phase right-lateral displacements on the Mt. Kumeta–Alcantara fault and left-lateral displacements on the Sangineto fault are consistent with the emplacement of the crystalline massif of Calabria onto the Apenninic chain. All the other strike–slip faults within the arc are also related to this process. Although along the Northern Calabria boundary and along the southern margin of the Sicily range right-lateral displacements occurred on NW–SE and E–W faults, and left-lateral displacements occurred on NE–SW faults a reverse of this pattern has been detected in the Iblean region. In Central and Southern Calabria compressive structures (folds and reverse faults) are found only along the external Ionian margin, while poorly-developed signs of wrench faulting are observed in the other zones where normal faulting prevailed.

The problems associated with the Late Pliocene–Pleistocene tectonic phase have been discussed already, but how this phase can be related to a deformation stage of the arc, and to what extent the present seismicity and volcanism of the arc reflect a continuing process is unresolved.

The scheme for the evolution of the arc which is proposed here envisages successive phases of deformation, in the Tortonian, Early–Middle Pliocene and Late Pliocene–Pleistocene.

Phase 1 *(Early–Middle Miocene).* The final stage of the Alpine emplacement of nappes in the Calabrian arc is characterized by the superposition of the crystalline Calabride units over the Apenninic–Maghrebid units

(Ogniben 1969, Vezzani 1973, Ogniben *et al.* 1975, Amodio-Morelli *et al.* 1976). The main contacts between the Apenninic and Alpine chains, which are still recognizable in the present distribution of the allochthonous crystalline masses of Alpine provenance, are the left-lateral Sangineto shear zone to the north and the right-lateral Taormina line to the south (Fig. 5a). The latter line is interpreted as synthetic conjugate fault to the right-lateral Mt. Kumeta–Alcantara shear zone, which was active in subsequent phases.

When attempting to restore the original trend of the arc, many hypotheses can be advanced. A post-Middle Miocene curvature of the structure is not accepted by some authors (e.g. Caire 1973, Schult 1976, Channell *et al.* 1980), as the shape of the arc could be also determined by the Early–Middle Miocene emplacement of the Calabria–Peloritani massif onto the African margin, thus producing anticlockwise rotations in the Southern Apennines and clockwise rotations in Western Sicily relative to the Iblean foreland (Catalano *et al.* 1976). It has however already been stressed that all the faults controlling the present arcuate shape of the structure were active from Tortonian to Pleistocene times and that they cut and disrupt the older boundaries (Ghisetti & Vezzani 1979a). An original rectilinear trend can therefore be accepted, considering that at present it is possible to recognize rotated blocks separated by transverse troughs whose trends are consistent with the bending of the arc and that, in the interior of each block, the older structural trends maintain their original rectilinear direction. Because in Central and Southern Calabria no evidence for wrench faulting has been found, it is possible to assume an original nearly N–S trend (still preserved in Southern Calabria) for the entire structure. This assumption is confirmed by the evidence for clockwise rotation of the Sicilian chain with respect to the stable Iblean foreland.

If an original N–S direction is assumed for the unrotated chain, it follows that the Sangineto shear zone was originally orientated NW–SE and that the Mt. Kumeta–Alcantara shear zone was originally NE–SW (see Fig. 5a).

Phase 2 (Middle–Late Miocene). During this phase the originally continuous N–S fold belt began to be segmented by the opening of longitudinal and transverse grabens

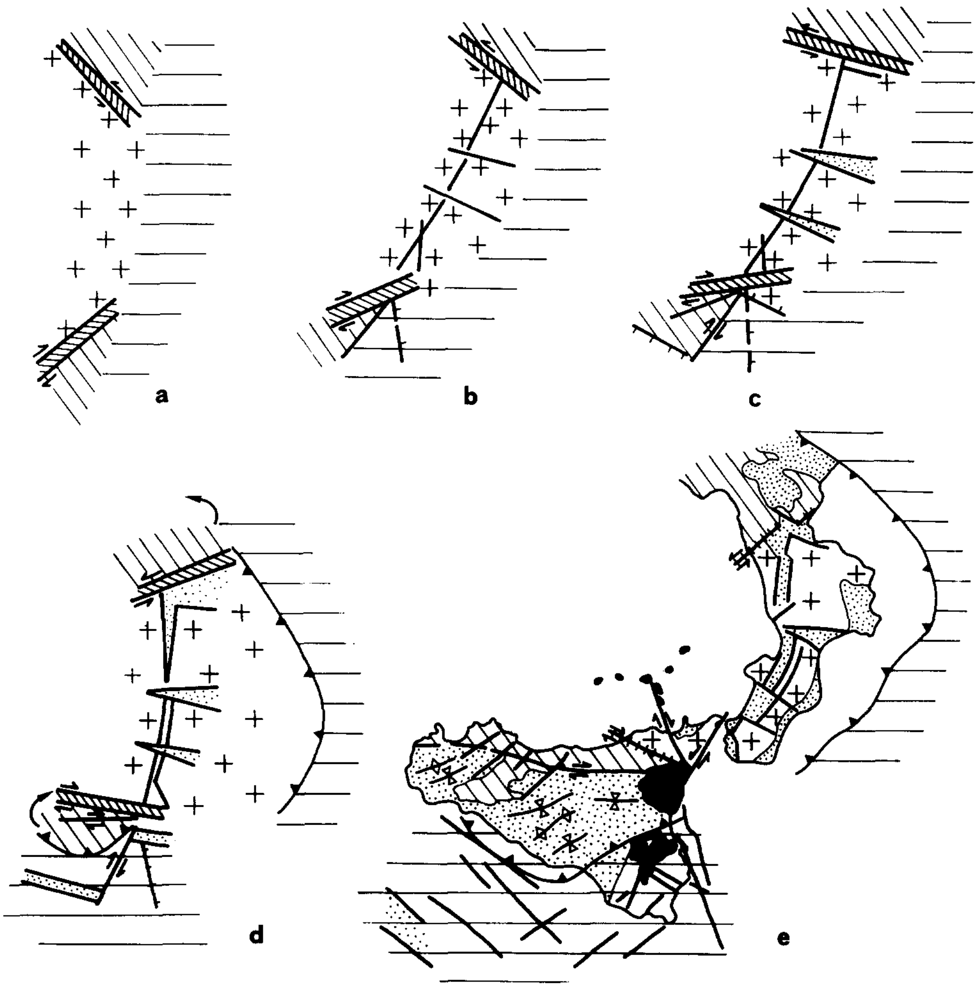

Fig. 5. A model for the progressive evolution of the Calabrian arc. Crosses, Calabria–Peloritani crystalline domain; oblique lines, Apenninic domain; horizontal lines, African margin; dots, post-orogenic basins; full black, volcanics; heavy lines, faults; coupled heavy lines with hatched ornament, Sangineto and Mt. Kumeta–Alcantara shear zones; heavy lines with black triangles, nappe fronts; heavy lines with open triangles, folds. (a) Early–Middle Miocene. (b) Middle–Late Miocene. (c) Early–Middle Pliocene. (d) Late Pliocene–Pleistocene. (e) Present setting of the arc. For full explanation see text.

largely confined between the two shear zones. The transverse grabens (Lower Crati, Catanzaro, Siderno, Reggio Calabria) are interpreted as being genetically related to a progressive bowing of the structure as a consequence of increasing shear along the Sangineto and Mt. Kumeta–Alcantara lines. Because of the opposed senses of rotation which were induced along the northern and southern margins of the arc, the whole area began to be dissected. This effect was probably related to the differential opening of the transverse grabens which became wider towards the Ionian sea (see e.g. the fan-like arrangement of the coastal lines in the Reggio Calabria graben). At the same time, and as a consequence of the superposition of the Calabrian massif on the Apenninic chain and foreland, the crust thickened (Morelli 1970) and an antiformal bending of Calabria resulted (Ortolani 1976). The bending was associated with the opening of the longitudinal grabens along thinned axial zones (Figs. 5b & c). Such a composite mechanism could explain the simultaneous development of grabens perpendicular to each other and intersecting where longitudinal structural trends are interrupted and rotated (Fig. 5c).

Phase 3 (Early–Middle Pliocene). During this phase the deformation of the structure continued and was characterized by increasing shear along the Sangineto and the Mt. Kumeta–Alcantara faults. The clockwise and anticlockwise rotations induced in Sicily and in the Southern Apennines respectively, completed the bowing of the arc and emphasized the fan-like opening of the transverse grabens, which at the same time rotated together with the entire structure (Fig. 5d). In this respect it has to be stressed that the overall bowing of the arc, inferred from the model of a rectilinear N–S belt, is identical to that which could be obtained by adding together the angular opening of each of the transverse troughs.

The mechanism which has been proposed may account for the apparently incongruous behaviour of different parts of the arc during the same phase, and in particular it may explain the lack of compressive structures in the central zones of the arc. The development of NE–SW folds and reverse faults in the external Ionian domain can be explained by invoking a compression which migrated eastwards. The greater uplifting rates in the external parts of the chain (Caltanissetta basin, San Arcangelo basin) relative to its axial zones (Peloritani, Nebrodi, Madonie, Southern Apennines) support such a suggestion.

The clockwise rotation of the Sicilian chain with respect to a stable Iblean foreland, whose unrotated character is confirmed by palaeomagnetic data (Channel *et al.* 1980), agrees with the present E–W trend of the Mt. Kumeta–Alcantara line, which was originally oriented NE–SW and was therefore nearly parallel to the Scicli–Ragusa fault zone (Fig. 6). Such a mechanism could also explain why the faults which at present display different orientations were active as right-lateral faults during the Early–Middle Pliocene phase, and why the progressive Plio–Pleistocene opening of the Gela–Catania trough was related to the process. The hypothesis implies an overall rotation of about 50° which is a substantial rotation to have occurred since Early Pliocene times (Ghisetti & Vezzani 1980).

Phase 4 (Late Pliocene–Present). The present configuration of the arc (Fig. 5e) was achieved during the Early–Middle Pliocene compressive phase, which completed the general rotation of the blocks. A change in the tectonic regime occurred during the Late Pliocene–Pleistocene, characterized by generally tensional tectonics. All the previously opened and subsided troughs continued to be sites of marine sedimentation in Pleistocene times, but they were uplifted as demonstrated by the distribution of the sedimentary facies and the generally regressive character of the sequence (Ghisetti *et al.* 1979). To the general tendency for uplift at unequal velocities in different blocks (Ghisetti & Vezzani 1979b, Ghisetti 1980) can be added the reactivation of normal faults of different orientations.

The regional uplifting of the arc may be considered as a final isostatic adjustment of a thickened crustal sector with a Moho depth of about 35 km in Sicily and Calabria, where the crust was doubled in thickness as a result of tectonic processes (Boccaletti & Manetti 1978). The area is bounded to the west by the foundered Tyrrhenian Sea, which constitutes a denuded area, characterized by a crustal thickness of intermediate type (Finetti & Morelli 1973) and by low free-air positive anomalies, which have been related to the sinking of a basin not yet in equilibrium (Colombi *et al.* 1973). In areas such as the Caltanissetta basin, where a minimum Bouguer anomaly of *ca* 100 mgals has been determined (Ogniben *et al.* 1975), the strong uplifting is reflected by the present height of a Lower Pliocene reference level (Ghisetti & Vezzani 1979b). The strong uplifting may be connected to an isostatic imbalance related to the elevated thickness of the sedimentary cover.

CONCLUDING REMARKS

Although the model presented here accounts for many of the observations, there remain some problems to be solved. For instance we do not yet know the total crustal shortening which is linked to the folding of the Miocene–Pliocene sequences of the Caltanissetta, San Arcangelo and Crotone–Spartivento basins. A rough estimate suggests a maximum shortening of about 30–40 km in the Caltanissetta basin, if shortening of 36% (Ramsay 1967) is assumed for the parallel-style folds of the area. In addition it is necessary to ascertain to what extent the neotectonic structures are related to the tectonics of the Iblean substratum, whose continuation beneath the Caltanissetta basin may be inferred. In the Caltanissetta basin (Gela–Catania trough excluded) no subsurface data are available, but it is well known for the Bradano trough in the Apulia–Lucania region that a Plio–Pleistocene nappe overrides the Plio–Pleistocene sequences of the Apulia substratum, the basal surface of detachment being identified in boreholes. As the Caltanisetta–Gela and San

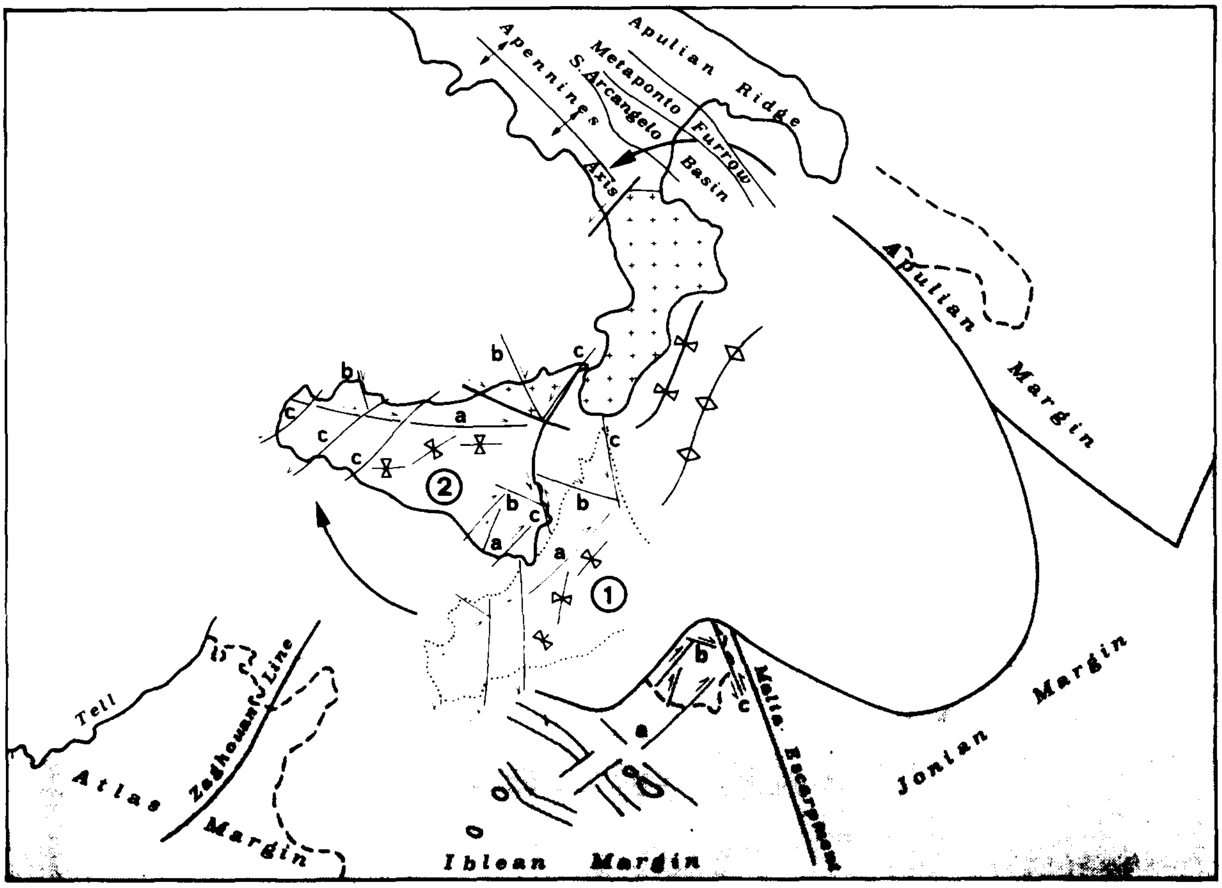

Fig. 6. Geodynamic evolution of the Calabrian arc. The darkened area shows the foreland margin and the dashed lines show the original position of the Apulian, Iblean and Atlas regions. 1, position of the thrust units of Sicily during the Middle Pliocene wrench fault phase; 2, present position of Sicily. Curved arrows indicate the clockwise rotation of Sicily and the anticlockwise rotation of the Apennines. For full explanation see text.

Arcangelo–Bradanic troughs seem to be connected with each other through the Crotone–Spartivento basins, a comparable tectonic situation may exist beneath Central Sicily. Thus the total shortening in the Caltanissetta basin could be greater than that inferred from the surface folds.

It therefore appears that the Crotone–Spartivento basins and the external Calabrian arc (Rossi & Sartori in press), which follow the curvature of the Calabrian arc (Fig. 4) are key areas within which it is necessary to know whether a connection exists between the external zones of the Southern Apennines. If this connection exists the Apulian and Iblean margins of the African plate must connect with each other through the Ionian margin.

It is therefore clear that many of the problems which have been briefly summarized are related and cannot be ignored in any comprehensive geodynamic interpretation of the Calabrian arc. Another problem which derives from the model is the proposed 50° rotation of the blocks of the arc since the Early Pliocene. Although a 50° rotation is supported by palaeomagnetic data, an alternative explanation has been put forward by Channell *et al.* (1980). They suggest that the observed rotation is due only to the relative displacements of different nappes during Early–Middle Miocene emplacement. However if we take note of the observation that the bowing of the Calabrian arc dissects and rotates blocks within which Plio–Pleistocene sequences are developed, a neotectonic genesis of the arc must be admitted.

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