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NEOTECTONIC EVENTS AND KINEMATICS OF RHEGMATIC-LIKE BASINS IN SICILY AND ADJACENT AREAS. IMPLICATIONS FOR A STRUCTURAL MODEL OF THE TYRRHENIAN OPENING

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Abstract: The last few Ma kinematic history of the Southern peri-Tyrrhenian orogenic belt has been reconstructed with the purpose of delineating a possible model of its recent geodynamic evolution. Unpublished field survey data, geophysical soundings, aerial photographic support and a review of literature have been utilised in order to propose a deep structural model of mainland Sicily and adjacent off-shore areas.

A review of the published geophysical data and the interpretation of some published seismic profiles, coming from the offshore areas, facilitate the neotectonic structural setting of the Central Mediterranean. The observed field geometries of the Sicily mainland, and a comparison with the marine data, are used to formulate a dynamic model, characterised by the development of several mega-shear systems, related to the northward Africa motion and active since the late Miocene–early Pliocene, superimposed onto a previous very complicated mobile belt geometries, that controlled the opening of several rhegmatic-like basins.

Abstrakt: W celu skonstruowania współczesnego modelu ewolucji południowego peri-tyrreńskiego pasa orogenicznego dokonano rekonstrukcji jego kinematycznej historii w ostatnich kilku milionach lat. Dostępne w literaturze dane geofizyczne i interpretacje profili sejsmicznych usytuowanych na Morzu Tyrreńskim umożliwiły poznanie neotektonicznej struktury centralnej części Morza Śródziemnego. Obserwowane na Sycylii struktury tektoniczne i ich porównanie z wynikami badań na obszarach morskich zostały użyte do skonstruowania dynamicznego modelu rozwoju licznych systemów wielkoskalowych ścięć (mega-shear) związanych z ruchem Afryki ku północy. Systemy te były aktywne od późnego miocenu do wczesnego pliocenu, oraz zostały nałożone na wcześniejszy bardzo skomplikowany mobilny pas strukturalny, który kontrolował otwieranie się basenów typu regmatycznego.

Key words: Neotectonic, Tyrrhenian, rhegmatic basins.

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INTRODUCTION

The Tyrrhenian Sea is interpreted as a basin with thin continental/oceanic crust, superimposed onto the Europe–Africa Collisional Thrust Belt since the late Miocene. Westwards, this basin is bordered by a fragment of the Alpine Belt (Sardinia and Corsica), and eastwards and southwards by the Apennine–Sicily Belt.

The large extension and the oceanization in the central parts of the basin and the attendant compression in the previous deformed Apennine–Sicily Thrust Belt, all related to the progressive spreading of the Tyrrhenian Sea, created in the Sicily mainland a complex sequence of alternating extensional and compressional tectonic events.

Some of field evidences, expressed by the neotectonic fault systems affecting the studied segment of the Central Mediterranean, show different trends and kinematic indicators, all related to Tyrrhenian stretching and evolution. The main trends that have been recognised are E–W, NW–SE and NE–SW All these cut the E–W trending Sicily Thrust Belt. The main NW–SE and NE–SW trending fault systems (generally with strike-slip movements) mostly outcrop in North and Central Sicily, where they stretch and/or truncate the previous compressive thrust imbricates of the Thrust Belt. These systems are explained as E–W trending strike-slip associated fault mega-riedels. Some of these recent structures, which outcrop more frequently, are interpreted as the result of different scale and strike-slip movements that have produced positive and negative flower structures cutting, in places, the previous compressional structures not older than 3 or 5 Ma (*Maghrebides Terrains*).

Moreover, along the Northern and Eastern Sicilian coastal areas, it is possible to observe a widespread presence of hanging-wall tilting low angle normal faults (listric faults), cutting the strike-slip fault systems. In Central Sicily, the prevalently E–W trending transcurrent faults are often buried, and recognisable due to the presence of many large scale en-echelon fold systems that involved the Plio-Pleistocene successions.

The exposed neotectonic structures represent the shallow evidences of deep geological mechanisms that controlled the recent evolution of the Peri-Tyrrhenian Belt. The related deep structures produced also different geophysical anomalies; the general trend of these parameters can help to understand the regional architecture of the analysed area.

Some tectonic phases recorded in the Plio-Pleistocene sequences have been recognised, pointing out the repeated change in time of their character (compressional/transpressional and extensional). The biostratigraphic data of the most recent sequences involved in the deformation have dated, in some places, the main neotectonic phases.

The comparison of the trend and significance of outcropping structures, carried out through the structural analysis and large-scale field observations, with those characterising the surrounding submerged areas of Sicily (recognised from the interpretation of already published high resolution seismic profiles already described), make it possible to fit all data in a structural model of the Tyrrhenian opening during the last 5–6 Ma.

The change in time of stress field, recorded in the polyphase deformed Plio-Pleistocene sequences, permits to hypothesise on rhythmical tectonics in Central Mediterranean related to a group of vectors in space that express several forces characterising the recent geodynamic evolution of the analysed area.

A possible model of the Tyrrhenian basin evolution given in this paper considers the widespread presence of strike-slip structures that might have controlled the basin formation and evolution, and the re-deformation of the pre-existing peri-Tyrrhenian Belt in the analysed area during the last few Ma.

TYRRHENIAN BASIN

GENERAL BACKGROUND

Two groups of models have been proposed for the Tyrrhenian Sea opening:

– vertical motion models, explained as the consequence of subcrustal erosion mantle mechanisms and intrusion of oceanic-type magmatism (Morelli, 1970; Selli, 1981, 1985; Heezen *et al.*, 1971; Selli & Fabbri, 1971), or large scale mantle diapiric upwelling ("krikogenic" model of Wezel, 1981, 1985);

– horizontal motion models based on the plate tectonics framework and on the occurrence of crustal strike-slip fault systems (back-arc type basin, Boccaletti & Guazzone, 1972; Dewey *et al.*, 1973, 1989; Alvarez *et al.*, 1974; Boccaletti *et al.*, 1976; Biju-Duval *et al.*, 1977; Boccaletti *et al.*, 1984; Rehault *et al.*, 1984a, b, 1987a; Kastens *et al.*, 1988).

GEOPHYSICAL DATA

Geophysical data from several projects (ODP, DSDP, CNR, ESCARMED) carried out in the last twenty years make it possible to define the deep architecture of the Tyrrhenian area. Fig. 1 shows a synthesis of the main results of published geophysical research in the Central Mediterranean (Morelli, 1970; Colombi *et al.*, 1973; Finetti & Morelli, 1973a,b; Morelli *et al.*, 1975; Lort, 1977; Schutte, 1978; Fabbri & Curzi, 1979; Panza *et al.*,1980; AGIP, 1981; Finetti, 1982; Steinmetz *et al.*, 1983; Della Vedova *et al.*, 1984; Req *et al.*, 1984; Finetti & Del Ben, 1986; Rehault *et al.*, 1987b).

The reconstructed physiography of the basin is characterised by a NW–SE trending bathial plain, more than 3,000 m deep, made up a discontinuous oceanic type crust and covered by Tortonian to Lower Pleistocene depositional sequences. Several NNE–SSW trending small basins, mostly filled by sedimentary sequences cut by volcanic dikes dissect the bathial plain. In major basins (Magnaghi, Vavilov and Marsili) many submerged volcanoes are located, aligned along a NW–SE trend, from the Sardinia scarp to the Aeolian Volcanic Arc. Towards the NW, the bathial plain is bordered by a very important structural lineament (Central Fault) that divides to the west the Cornaglia Terrace and the Sardinia Basin. Southwards and southeastwards, the bathial plain passes into a number of small basins (Erice, S. Vito, Cefalù, Orlando, Gioia, Paola; Fabbri *et al.*, 1981; Wezel *et al.*, 1981), superimposed on the strongly deformed carbonate and siliciclastic sequences of the Sicily–Apennine Thrust Belt, and filled by the Plio-Pleistocene clastic sequences. The age of the lowermost depositional sequences filling these basins youngs towards the E and SE.

The deep basinal area gradually passes to the Sicilian Shelf, where the previously described small basins are recognised. These are mostly the result of half-graben formation and, in places, of inversion structures involving Pleistocene deposits (Fabbri *et al.*, 1981; Wezel *et al.*, 1981). Some emergent volcanic cones (Ustica and Aeolian Islands) are also present in this area.

The measured heat flow (Della Vedova & Pellis, 1979; Della Vedova et al., 1984, 1991) indicates different provinces and three maxima corresponding to the Magnaghi–Vavilov–Marsili area (more than 200 mW/m^2), while a minimum characterises the Poseidone–Marsili and the De Marchi–Magnaghi–Vavilov Seamounts (less than 50 mW/m^2). The heat flow gradually decreases from the central part of the Tyrrhenian basin towards the peripheral areas (less than 100 mW/m^2 towards Tuscany, 100 mW/m^2 in the Sicily–Calabria–Campania coastal areas and 50 mW/m^2 in the eastern Sardinia shelf). In the peninsular Italy, the heat flow values indicate two maxima corresponding to recent volcanic activity in Tuscany and in the Campania margin (Palinuro area).

Gravimetry (Morelli, 1970; Colombi *et al.*, 1973) indicates the existence of two positive highs (more than 200–250 mgal) corresponding to the Magnaghi, Vavilov and Marsili areas. Southward, the gravimetric values decrease regularly with a minimum corresponding to the central part of Sicily (between 0 and −100 mgal in the Caltanissetta Basin). Minor positive anomalies characterise the Northern Sicily offshore (Drepano Seamount and Ustica–Aeolian Islands). Gravity values again increase towards the Ionian Sea (Morelli *et al.*, 1975; Rossi & Sartori 1981; Makris & Stobbe, 1984; Rehault *et al.*, 1987b). Between these two areas, an arc-shaped low anomaly zone coincides with the Tertiary sedimentary basins of the Sicilian–Southern Apennines Belt (Caltanissetta Basin, External Calabrian Arc and Bradanic Trough).

The Moho discontinuity (Schutte, 1978; Finetti, 1982; Steinmetz *et al.*, 1983; Req *et al.*, 1984; Finetti & Del Ben, 1986; Rehault *et al.*, 1987b; Locardi & Nicolich, 1988) elevates in the Magnaghi–Vavilov and in the Marsili areas (less than 10 km below sea level), where the crustal thickness is less than 7 km. In these areas, seismic studies (Recq *et al.*, 1984) indicate the presence of oceanic-type crust. The Moho discontinuity descends towards the peri-Tyrrhenian sectors as far as the foreland (Hyblean and Apulia), where its deepest value has been calculated at 25–35 km. Under the southern Calabrian–Maghrebian Belt, the Moho discontinuity trend indicates a crustal superposition of the Tyrrhenian–Calabrian (35 km Moho depth) onto the Ionian microplate (Schutte, 1978), where the Moho is 20 km deep. Some strong Moho vertical discontinuities can also be observed in the peri-Tyrrhenian areas (as visible, for example, in Fig. 1, where between 12°–12.5° and 13.5°–14° E long some N–S trending discontinuities cross the Sicily area to the central part of the basin).

The Wadati-Benioff surface depth (Caputo *et al.*, 1972; Panza *et al.*, 1980) is relatively shallow under the Northern Sicily–western Calabria coastal areas, but it rapidly increases owing to strong verticalization in the Aeolian area, as geochemical-volcanological and petrographic studies have proved (Barberi *et al.*, 1974; Villari, 1980; Locardi, 1985).

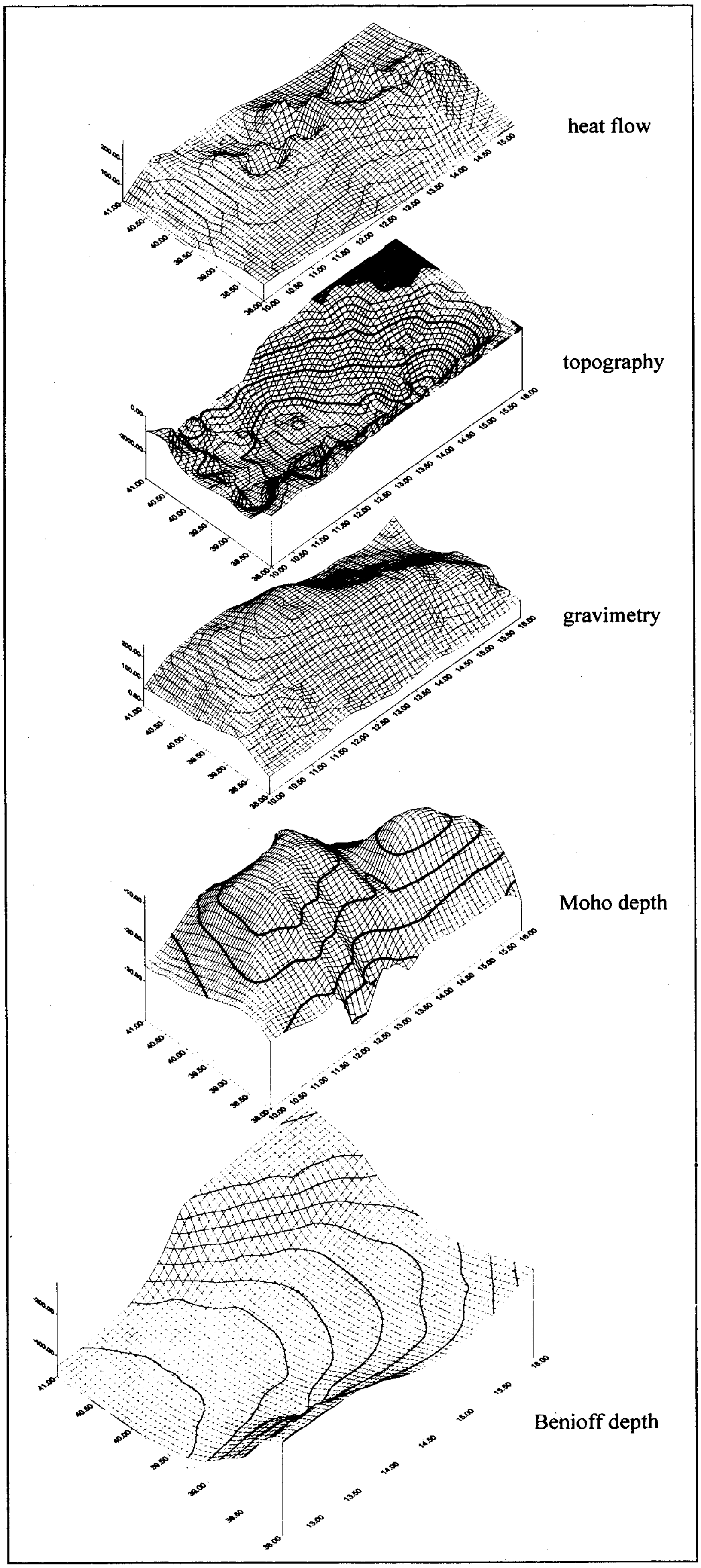

Fig. 1. Main physical characteristics of the Tyrrhenian area. Data from: Morelli (1970), Colombi *et al.* (1973), Lort (1977), Schutte (1978), Panza *et al.* (1980), Steinmetz *et al.* (1983), Della Vedova *et al.* (1984, 1989), Req *et al.* (1984), Duschenes *et al.* (1986), Finetti & Del Ben (1986), Rehault *et al.* (1987b). See text for explanation

STRUCTURAL SETTING OF THE SICILY THRUST BELT

The main tectonic domains characterising the Central Mediterranean, that may be recognised on land and under the sea around Sicily (Fig. 2), are (from the south):

– an undeformed, or weakly deformed foreland extending from north-eastern Tunisia to south-eastern Sicily and partly inflected below;

– the strongly deformed Sicily Belt, trending E–W from the Egadi Islands to the Malta Escarpment, and northwards as far as the Southern Sardinia Channel;

– the Kabilias and the Calabrian–Peloritani Arc forming the submerged Drepano Smt. (Compagnoni et al., 1986) and the Elimi Chain (Beccaluva *et al.*, 1984), interpreted as an intermediate element in the African Maghrebide–Sicily–Apenninic Belt;

– the European–Sardinia Domain (Auzende *et al.*, 1974; Barberi *et al.*, 1984) thrust over the submerged Kabilo–Calabrian domain.

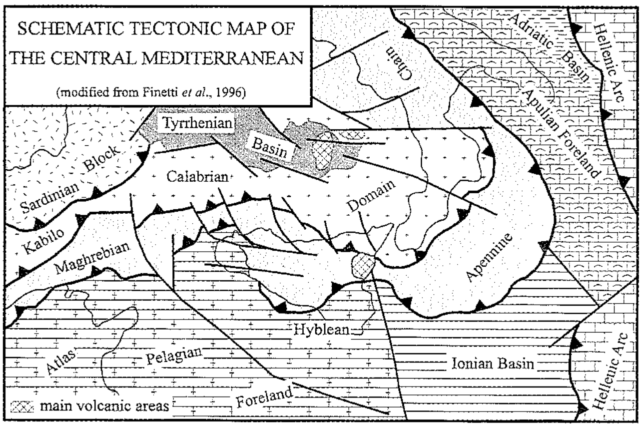

Fig. 2. Schematic tectonic map of the Central Mediterranean

Two tectonic piles, derived from the deformation of different African palaeogeographic domains, characterise the western and the eastern sectors of the Sicilian Belt (for recent lithologic columns, with indicated periods of tectonism see Catalano *et al.*, 1993b).

The Eastern Sicily Belt consists of several thrust systems made up (from the top) of:

1 – a set of prevalently Hercynian crystalline tectonic units of the Peloritani sector of the Calabrian Arc;

2 – several tectonic units of Cretaceous to Paleogene flysch-like sequences (Flysch di Monte Soro);

3 – several tectonic units of very strongly deformed Cretaceous claystones and "Sicilidi Variegated Shales";

4 – several tectonic units of Oligocene to Miocene foreland siliciclastic turbidites (Flysch Numidico);

5 – some prevalently Triassic to Neogene carbonate tectonic units (Panormide domain-derived structural units);

6 – several tectonic units consisting of Triassic to Neogene basinal sequences (Imerese domain-derived structural units);

7 – several tectonic units formed by Mesozoic to Tertiary basinal carbonatic sequences (Sicanian domain-derived structural units).;

8 – the deepest element of the Eastern Sicilian Belt, formed by prevalently Oligocene to Miocene clastic sequences, Messinian evaporites and Pliocene to Pleistocene basinal sequences ("Gela Thrust System"; Catalano *et al.*, 1993b.).

9 – the gently deformed Hyblean foreland.

From the top, the geometry of the Western Sicily Belt is due to the superposition of:

1 – several tectonic units derived of deformation of the "pre-Panormide" domain;

2 – a set of tectonic units prevalently consisting of Triassic to Neogene carbonates, derived from deformation of the Panormide domain;

3 – several tectonic units made up of Triassic to Neogene basinal sequences, derived from deformation of the Imerese domain;

4 – another set of tectonic units of Triassic to Neogene prevalently carbonatic sequences derived from deformation of the Trapanese domain;

5 – several tectonic units composed of Mesozoic to Tertiary basinal carbonatic sequences, derived from deformation of the Sicanian domain;

6 – the Meso-Cainozoic deformed foreland (Saccense domain-derived tectonic units);

7 – the Gela Thrust System.

Fig. 3 shows two simplified deep structural sections across the western and eastern Sicily. The structural style recently recognised in the island is comparable to the thin-skinned deformational model; the overall folds and thrust belt show ramp and flat geometries, different duplex levels, some regional-propagated detachment surfaces, and a marked disharmonic folding. A multiduplex configuration has also been recognised in different sectors of the Sicilian chain (Lentini *et al.*, 1990; Catalano *et al.*, 1993b), as well as in the surrounding submerged areas (Catalano *et al.*, 1993c).

In the deep structural sections (Fig. 3), the main palaegeographic domains-derived tectonic units are represented, together with the main "out-of-sequence" low angle reverse faults (ϕ), that may be the result of *back-stop*-like processes, probably active since the Langhian (age of sequences overlying the back-thrusted "Antisicilidi units"). Out-of-sequence faulting repeated the previous deformed tectonic complex and might have produced the subsequent superposition of the more external units (*e.g.* Panormide units) over the most internal ones (Fig. 3B), as well as the Trapanese units over the Sicanian units.

OLIGO-MIOCENE KINEMATICS AND THE BACK-STOP MODEL SUPPORT FOR THE SICILY BELT

The kinematic history of the Sicilian Maghrebides is comparable to the thrust envelopment model in the literature. During the Miocene, the collisional processes induced the deformation of the African domains, expressed by the activation of some thrust families linking in different de-

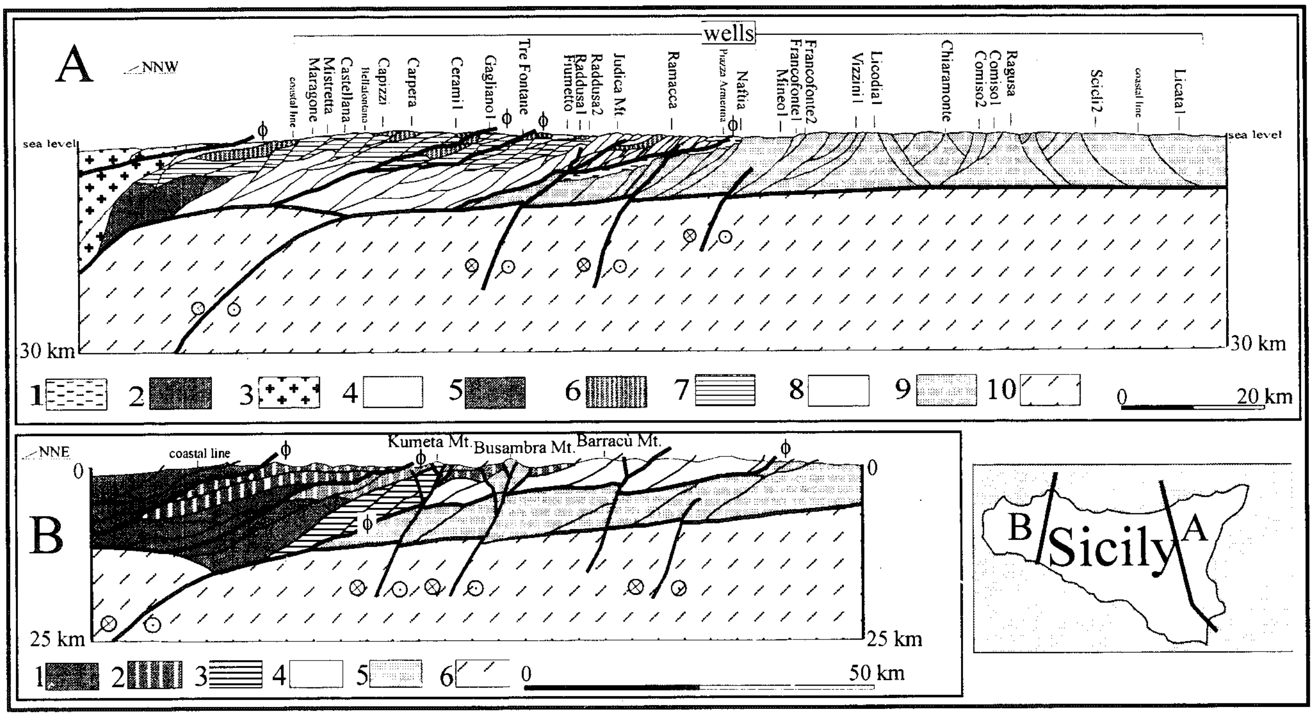

Fig. 3. Crustal sections across Eastern (**A**) and Western Sicily (**B**). **A.** *1* – Plio-Pleistocene clastic units; *2* – "Gela Nappe"; *3* – Peloritani crystalline units; *4* – Sicilide Monte Soro units; *5* – Panormide units; *6* – Sicilide Troina units; *7* – Numidian Flysch; *8* – Sicanian units; *9* – Hyblean foreland; *10* – crust. **B.** *1* – Panormide units; *2* – Imerese units; *3* – Trapanese units; *4* – Sicanian units; *5* – Saccense units; *6* – crust. ϕ – main out-of-sequence low angle reverse faults. The thick lines are the main high-angle buried and emergent regional-trending transpressional faults

tachment surfaces along the original Sicilian multilayer. During this kinematic stage disharmonic folding occurred, which is generally represented by isoclinal geometries in the less competent Liassic to Tertiary basinal sequences, and more gentle (mostly ramp anticlines) in the Triassic to Liassic carbonate platform sequences. During a later kinematic stage, another and deeper piggy-back thrust sequence cut the previous multiduplex, producing more and more cut-off relations.

During the Africa–Europe collision, the occurrence of *back-stop*-like processes might be supposed (see Fig. 3). Field evidences in eastern Sicily are the regional backthrusting of the "Antisicilide Nappe" over the previously deformed Peloritani element during the Early Langhian, as well as the Sicilide Nappe over the Oligo-Miocene Numidian Flysch in north-central Sicily. With this interpretation, the Sicilide and Antisicilide sequences can be regarded as the Cretaceous to Paleogene filling deposits of the Sicanian basin and its eastward prolongation.

The crustal doubling (delamination) and the vertical discontinuities, as supported by the deep geophysical data from the Baglio Inclusa and Alcamo areas (Colombi *et al.*, 1973; Giese & Reutter, 1978), and surrounding areas (Cassinis *et al.*, 1969; Morelli *et al.*, 1975; Schutte, 1978), might have determined until the Pleistocene the emplacement of the Gela Thrust System (in this paper, it is northward extended versus the buried Sicanian wedge and its detached Cretaceous to Miocene covers) of the Sicanian Thrust System over the gently deformed foreland (Hyblean and Saccense domains).

NEOTECTONIC FIELD DATA OF THE SICILY MAINLAND

The neotectonic structural grain of Sicily mainland is represented by different geometries related to compressional, transcurrent and extensional deformational stages.

THRUST TECTONICS

Plio-Pleistocene thrust geometries characterise the Northern and Central Sicily mainland. In Northern Sicily, the thrusting is expressed by enveloped-like geometries involving Messinian–Early Pliocene deposits (Figs. 5 and 6), while in Central Sicily the thrust pile is represented by the "Gela Thrust System" auctorum (Fig. 10B). The Plio-Pleistocene thrust sheets are cut by more recent dip- and strike-slip fault systems.

STRIKE-SLIP TECTONICS

It is possible to define many of the most recent structures characterising the Sicily mainland as the result of large-scale strike-slip motions. These structures, at length recognisable in the island, express a regional, prevalently E–W trending strike-slip dextral system with associated mega-riedels (Fig. 13). The recognised associated structures are prevalently brittle and subordinately ductile structures (Figs. 8–10).

Several field observations indicate that the outcropping neotectonic brittle structures consist mostly of fault systems

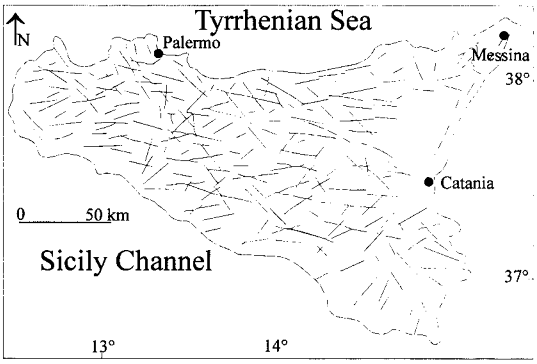

Fig. 4. Main neotectonic brittle lineaments characterising mainland Sicily

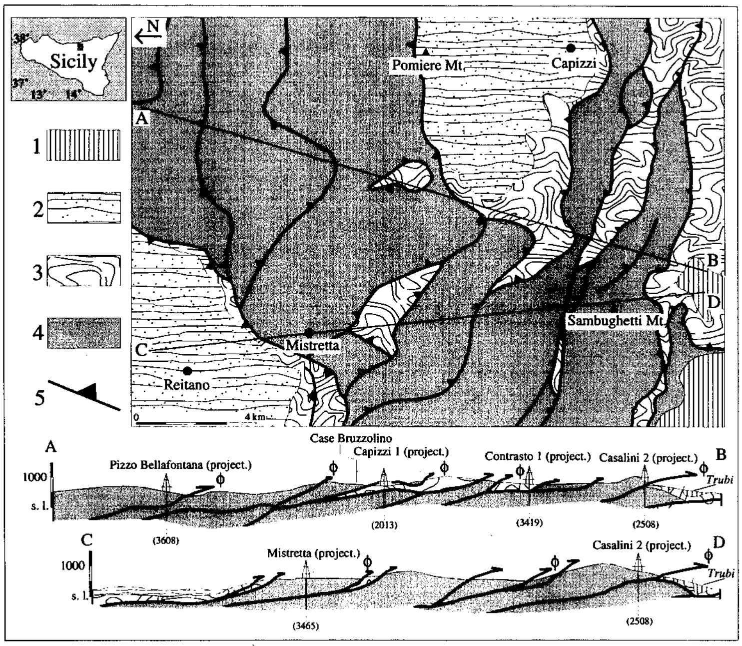

Fig. 5. Geological map and sections across the Nebrodi Mts. tectonic edifice of which the thrust system (ϕ) involving Pliocene sequences ("Trubi") is recognised. *1* – Early Pliocene "Trubi" Fm.; *2* – Oligocene–Early Miocene flysch-like Reitano Fm.; *3* – Cretaceous-to-Paleogene Sicilidi terranes; *4* – Oligocene–Early Miocene Numidian Flysch; *5* – main thrusts

with different kinematic indicators (dip- and strike-slip). The fold systems that have also involved the outcropping Plio-Pleistocene sequences appear as large-scale and gentle en-echelon systems, relatable to some buried and emergent transcurrent faults. Fig. 4 shows a synthesis of aerophotographical observations in Sicily and the main brittle neotectonic trends of the lineaments characterising the island. Figs. 7 and 8 show some examples, based on field observations, of recent structures characterising western and eastern Sicily. The regional trend of brittle structure allows to consider the whole system as deep-seated down to the crustal levels that represent the African regional monocline (Fig. 3).

Several examples based on field observations allow to hypothesise the presence of important crustal structural elements in the Sicily mainland.

The example in Fig. 7A is a sketch of large-scale neotectonic structures involving the previously deformed Western Sicily Belt. Two NW–SE to E–W trending high angle reverse (transpressive) faults that have produced some positive flower structures (Kumeta and Busambra Mts.) are represented in the figure. In these areas, the most recent sequences involved in the deformation related to the positive flower structures are Late Pliocene (*G. inflata* biozone) and appear to be not older than 2.4 Ma, and certainly not earlier than 1.2–1.4 Ma in the Calatubo area, as illustrated by Agate *et al.* (1993) in the Northern Sicily offshore areas.

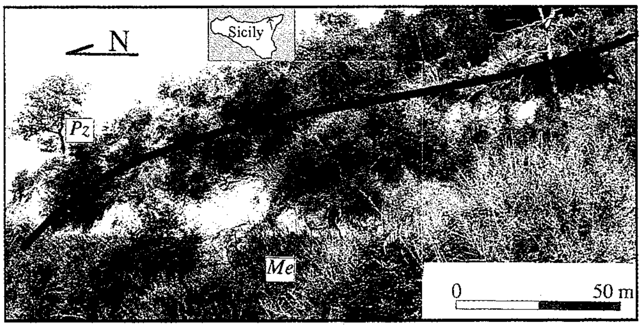

Fig. 6. Example of post-Messinian thrusting recognised in the more internal mainland Sicily areas (Peloritani Mts.). *Pz* – pre-Triassic Aspromonte Unit (high-grade crystalline rocks); *Me* – Messinian gypsum

Fig. 7B represents the neotectonic structural setting of the Palermo area. The sketch illustrates:

– an E–W trending dip-slip fault system cutting a sandstone sequence of Sicilian age (*G. truncatulinoides excelsa* biozone);

– a previous extensional fault system represented by a N–S trending symmetric graben (in the Monreale area);

– an E–W trending asymmetric graben (in the Belmonte Mezzagno area), where two opposite-verging structures are separated by a NNW–SSE trending high angle strike-slip "transfer" fault. Comparison with marine data from interpretation of high-resolution multichannel seismic reflection profiles (Agate *et al.*, 1993) makes it possible to date the earliest extensional deformation at between 1.2–1.4 and 0.8 Ma.

Fig. 7C shows a NE–SW trending large scale gentle en-echelon fold system involving Pleistocene marine sequences. These structures could be interpreted as a shallow expression of an E–W trending buried right-lateral transcurrent fault, which northwards has produced a buried positive flower structure and a system of partially emergent syntethic macroriedels (Castelvetrano area). The age of the most recent successions involved in the folding is Lower Pleistocene (*G. cariacoensis–G. truncatulinoides excelsa* biozones).

In the Sicani Mts. Area, it is possible to suppose the presence of a partially buried shear zone. The right-lateral displacement of this crustal structure could have produced a system of E–W trending, high-angle branched transpressive faults and associated meridionalls-trending riedels. Outcrop data confirm this supposition. Fig. 7D shows an analogous configuration. In this area, outcropping Mesozoic sequences

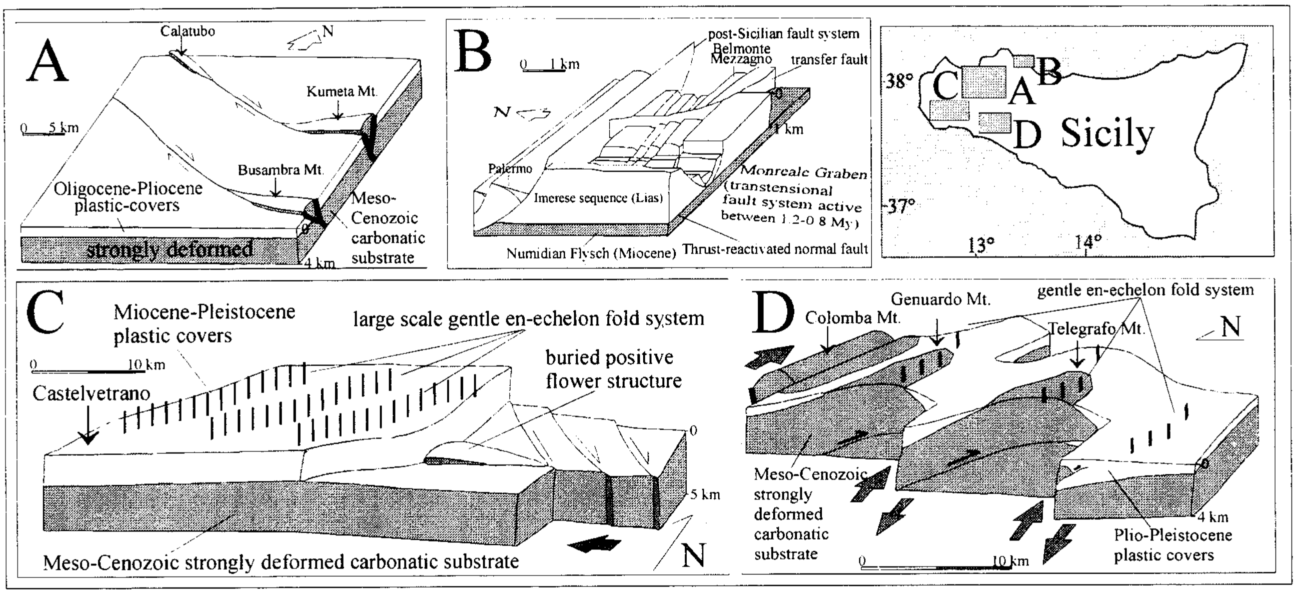

Fig. 7. Examples of neotectonic structures outcropping in Western Sicily. See text for explanation

are deformed by a NW–SE trending fold and thrust system, by an E–W trending right-lateral transcurrent fault and also, together with the Pleistocene sequences (*G. cariacoensis* biozone), by a NE–SW trending large-scale gentle en-echelon fold system. In this case, the erosional surface was produced by the "emersion" of the previous strongly deformed Mesozoic substrate (Colomba and Genuardo Mts. ramp anticlines) during the Pleistocene tectonic phase.

The examples from Eastern Sicily (Fig. 8) reveal that the neotectonic features are again represented by fault systems with dip- and strike-slip kinematic indicators.

The NW–SE trending strike-slip fault systems are prevalently present in the northern coastal area and cut the E–W trending Thrust Belt (Fig. 8A). Eastwards, the strike-slip fault systems are associated with an en-echelon fold system that reoriented the previous strongly folded and faulted sequences. Fig. 8B shows an example of these structures; the block-diagram indicates the trends and arrangement of the most important neotectonic large-scale folds and faults found in the westernmost sector of the Peloritani tectonic edifice, where the Mesozoic to Tertiary sedimentary covers (Longi-Taormina Unit) mostly outcrop. In the map view, the neotectonic gentle en-echelon fold system (thick lines) that reoriented the previous system (thin lines) can be observed. The dashed line represents the emergent transcurrent fault of the block-diagram. The fault system cuts a very recent arenaceous sequence in the coastal area. A comparison with geophysical data from the offshore areas (Fig. 9) makes it possible to date the transpressional events at 1.4 Ma.

An example of the neotectonic structural setting of the NE Sicilian areas is shown in Fig. 8C. In this area (Patti–

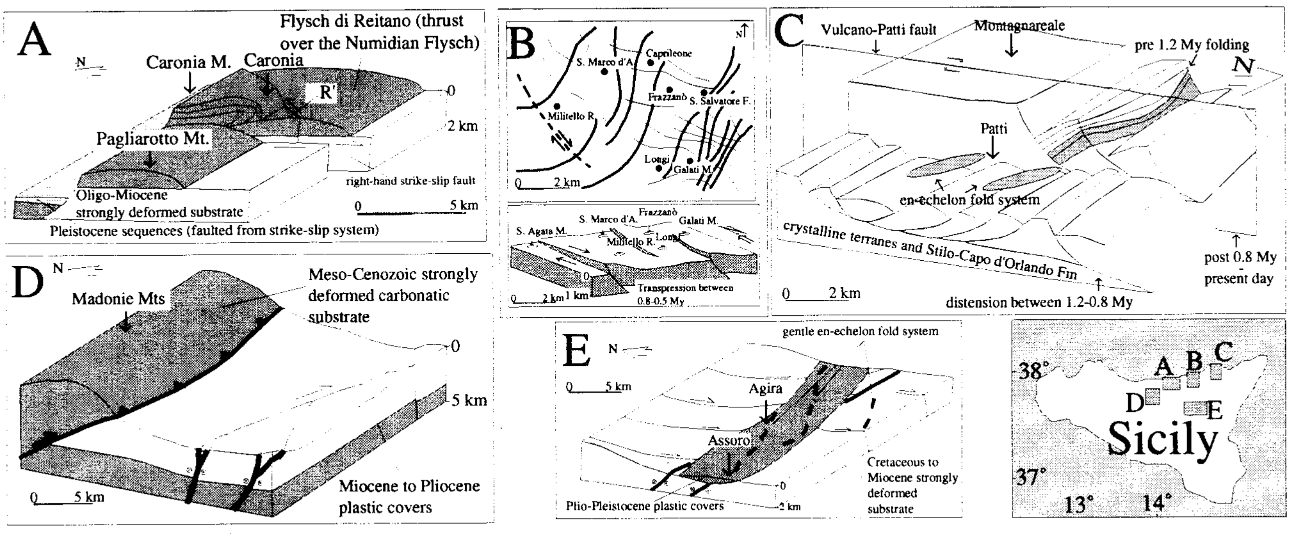

Fig. 8. Examples of neotectonic structures outcropping in Eastern Sicily. See text for explanation

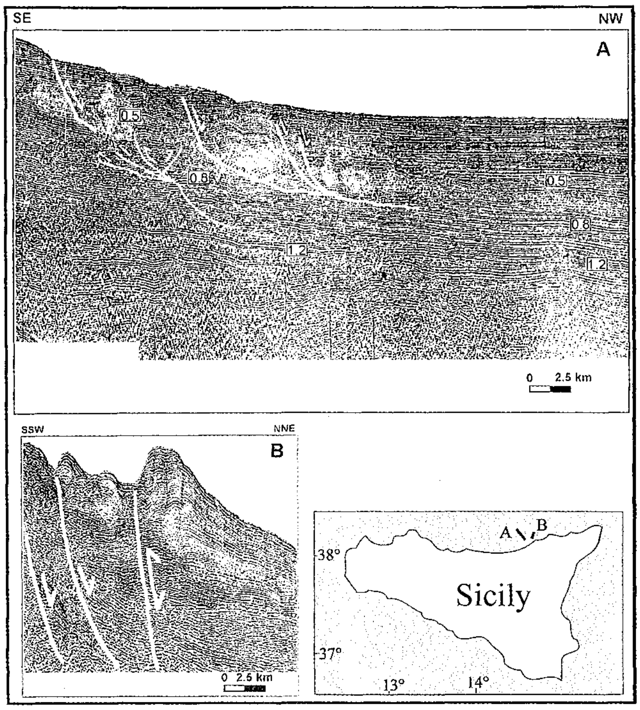

Fig. 9. **A.** High-resolution seismic profile showing the low-angle normal fault system cutting the Pleistocene sequences. Attempt of sequence stratigraphy distinguishes some depositional sequences in the sedimentary successions. Sequence boundaries permit to date deformation events. **B.** Seismic section shows evidences of inversion (or transpression) tectonics affecting the Plio-Pleistocene sequences in the Eastern Sicily offshore From Nigro & Sulli (1995)

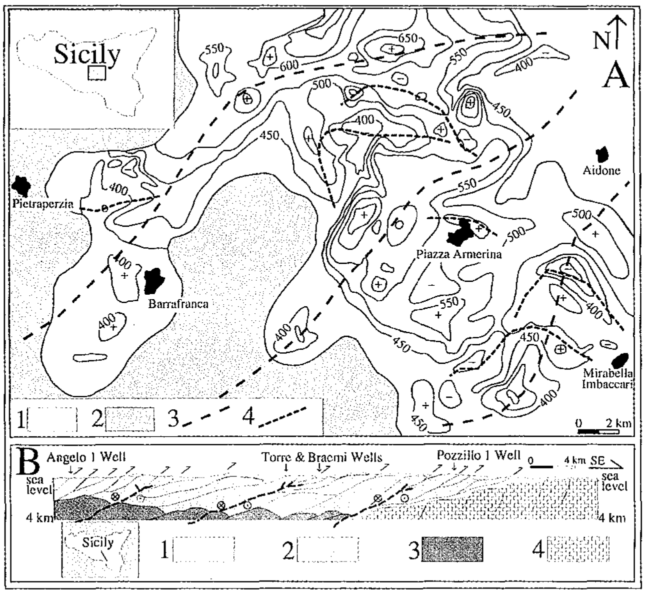

Fig. 10. **A.** Map view of the top of Late Pliocene–Early Pleistocene sequences exposed in Central Sicily. Thin lines indicate the altitude above sea level. *1* – Plio-Pleistocene sequences; *2* – pre-Middle Pliocene sequences; *3* – axes of folds involving the overall outcropping sequences; *4* – axes of folds involving only the Late Pliocene and the pre-Pliocene sequences. **B.** Simplified structural section across Central Sicily. Dashed lines indicate the supposed buried right-lateral transcurrent fault system that may have affected the region. *1* – Plio-Pleistocene sequences; *2* – Gela Nappe; *3* – Sicanian units; *4* – Hyblean foreland

Montagnareale) we can reconstruct the tectonic history of the last 1–1.5 Myr. The outcropping Pleistocene shallow-water sequences (*G. inflata–G. cariacoensis* biozones in the Patti Marina area) are gently folded and covered by very shallow sequences of Sicilian age (*G. truncatulinoides excelsa* biozone). The entire sequence was subsequently faulted and tilted northwards In the Patti area, an asymmetric graben was produced, while the listric geometries of the fault system are revealed by block tilting. This system was subsequently cut by a N–S trending, right-lateral strike-slip fault determining the en-echelon folding of the more recent outcropping sequences (*G. cariacoensis–G. truncatulinoides excelsa* biozone).

The predominance of faults decreases towards the south, where Cretaceous to Miocene plastic covers (flysch-like sequences) and Pliocene–Pleistocene marine deposits crop out. Also, in this part of the region, the NE–SW trending large scale gentle en-echelon fold systems, interpreted as field evidence of a buried E–W trending right-lateral deep transcurrent fault system, can be observed (Figs. 8D and 8E).

En-echelon fold systems are also present in central Sicily. In this area, unpublished geophysical data from geoelectrical sounding surveys with quadripolar Schlumberger configuration, make it possible to reconstruct the top geometry of the Late Pliocene–Early Pleistocene sequences. As illustrated in Fig. 10A, the Plio-Pleistocene sequences are polyphase folded, creating dome and basin geometries. In the Butera area, arenaceous Pleistocene sequences (*Gephyrocapsa* biozone) are affected by the second of these two fold systems, the NE–SW trending one (Fig. 10). Neotectonic structures also characterise the most stable geological area outcropping in Sicily (Hyblean region, SE Sicily). This part of Sicily represents the gently deformed foreland of the Neogene to Pleistocene collisional belt. Several thick carbonate sequences of a Mesozoic–Tertiary age outcrop in this area. Carbonate bodies are locally very gently folded and bounded by very recent fault systems revealing a prevalently distensive-transtensive displacement (Ghisetti & Vezzani, 1981a; Ben-Avraham *et al.*, 1987; Grasso & Reuther, 1988, 1990, 1992; Grasso, 1993).

The Hyblean element is overthrust by the frontal part of the Sicily Chain (Gela Thrust System), its emplacement having started during the Plio-Pleistocene.

The tectonic setting of this part of Sicily is also characterised by some neotectonic "lineaments" which are a clear expression of the emergent and buried strike-slip fault systems regionally trending E–W to N–S, with some different displacements.

Towards the NW, the Hyblean element is also bordered by an extensional (probably transtensional) NE–SW, NNE–SSW and WNW–ESE trending fault systems (Ghisetti & Vezzani, 1981a), separating the foreland from the frontal part of the Sicily Chain and the recent "Gela-

Catania Foredeep", connecting to the Malta escarpment. This trough, filled by Plio-Pleistocene sequences, can be interpreted as a graben-like structure located between the Caltanissetta Basin and the Hyblean Plateau.

Finally, the Ragusa zone is characterised by another right-lateral transcurrent fault system of regional significance. This is evidenced by sheaves of faults bounding a N–S trending master mechanical discontinuity, interpreted as associated large-scale riedels. The Ragusa fault runs parallel to another fault system located in Syracuse, extending southwards to the Malta–Medina areas.

EXTENSIONAL TECTONICS

Along the Northern and Eastern Sicilian coastal areas, a widespread occurrence of hangingwall tilting low-angle normal faults (LANFs, Figs. 11A,B,C and 12) with the Tyrrhenian vergence, cutting the strike-slip fault systems, has been observed. These LANFs cut the E–W trending tectonic edifice, creating a large extension and increasing the accommodation space in half-grabens and in small basins located between the main tilted blocks.

Offshore, a progressive eastward decrease in Pliocene package thickness, and an increase in Pleistocene thickness, can be observed (geological interpretation of multichannel high-resolution seismic lines, Fig. 12; Wezel *et al.*, 1981; Sartori, 1990).

REGIONAL SIGNIFICANCE OF NEOTECTONIC FIELD DATA

The widespread presence of post Messinian–Pliocene thrusting in the Northern Sicily Chain leads to the following considerations:

– The recognised geometries appear comparable to the tectonic style characterising the Southern Sicily and its offshore (Bianchi *et al.*, 1987; Argnani, 1993 and literature therein; Catalano *et al.*, 1993a, b), where the so called "Gela Nappe" outcrops;

– the thrust sheets that form the Gela Nappe, piled up since the Middle Pliocene, are prevalently made up by Numidian and Sicilidi sequences and by Late Miocene–Early Pleistocene deposits (AGIP well data of Pozzillo 1 and Manfria 1), and thrust over the Pleistocene sequences in the southern offshore areas. "deep" Pliocene horizons thrusted by Mesozoic carbonates are also known in the Western Sicily (e. g. Cammarata well).

Thus, the analysed Nebrodi Mt. area appears to form the innermost portion of the outcropping Gela Nappe and, according to Ghisetti & Vezzani (1982), represents the shallow expression of the general reactivation of the Eastern Sicily Chain due to deep compressional mechanisms related to the late-collisional involvement of crustal levels, as also proved by the geophysical data of Schutte (1978).

Also, in Northern Sicily, several neotectonic discontinuities related to the Tyrrhenian dynamics are located, cutting the post-Messinian thrust surfaces. The neotectonic fault systems (mostly with strike-slip kinematic indicators) related to the Tyrrhenian stretching, showing E–W, NW–SE and NE–SW trends cut the E–W trending North Sicily Thrust Belt (Ghisetti & Vezzani, 1977). The latter fault systems merge along the E–W trending transcurrent systems and are interpreted in this paper as regional trending associated Riedel systems. The main NW–SE and NE–SW trending strike-slip fault-riedels, mostly outcropping in Northern Sicily (Figs. 7A, 8A-B-C-E, 13), stretch and/or truncate the previous compressive thrust imbricates, and ramp anticlines of the Sicily Chain.

In Western Sicily, the most important outcropping E–W trending transpressional structures have field evidences in the Kumeta Mt. and Busambra Mt. areas, where it is possible to recognise the described large-scale ramp anticlines cut by subsequent high angle reverse faults that have established some asymmetrical positive flower structures (Fig. 7A). These structures, which involved a previous strongly deformed substrate (Trapanese domain-derived sequences), are interpreted as a shallow evidence of deep shear zones, related to the westernmost Moho vertical discontinuities that have produced associated shallow riedels (see Fig. 1). Eastwards, a local change of direction might have determined a number of connecting transtensile structures related to a torsional deformation and an overprinting of large-scale rhegmatic-like geometries in the Caltanissetta Basin auctorum (Fig. 13). This is shown in Fig. 10, where the en-echelon geometries could indicate the existence of an E–W trending structural line and might be interpreted as the shallowest evidence of a buried right-lateral transcurrent fault system affecting the western subsurface prolongation of the Hyblean Foreland below the Gela Thrust System and the Meso-Cainozoic deformed substrate (Sicanian domain). It is likely that this trend extends westwards in the Sciacca area.

Northwards, the Caltanissetta Basin is bordered by an important right-lateral strike-slip fault system having a regional E–W trend (Kumeta–Alcantara and Alia–Malvagna lines of Ghisetti, 1979a and Ghisetti & Vezzani, 1982). The Kumeta–Alcantara and Alia–Malvagna tectonic lineaments bound the Northern Sicily coastal area which, during the Plio-Pleistocene, was affected by a very strong uplift (Ghisetti, 1979b).

The E–W trending transcurrent buried and emergent faults (and the associated NE–SW and NW–SE trending synthetic and antithetic riedels) found in western and eastern Sicily, may be interpreted as intraplate migrating shear systems related to the NW–SE-directed Tyrrhenian spreading and to the adjacent Ionian subduction complex (Ghisetti & Vezzani, 1981b). Locally uneven trend of these systems could have produced flower structures (*e.g.* Kumeta and Busambra Ridges), neotectonic axial culminations (*e.g.* Castelvetrano and Sciacca Ridges), structural depressions derived from torsional deformations (*e.g.* Caltanissetta Basin) and/or pull-apart offshore basins (*e.g.* Pantelleria Rift, Medina Graben, etc.).

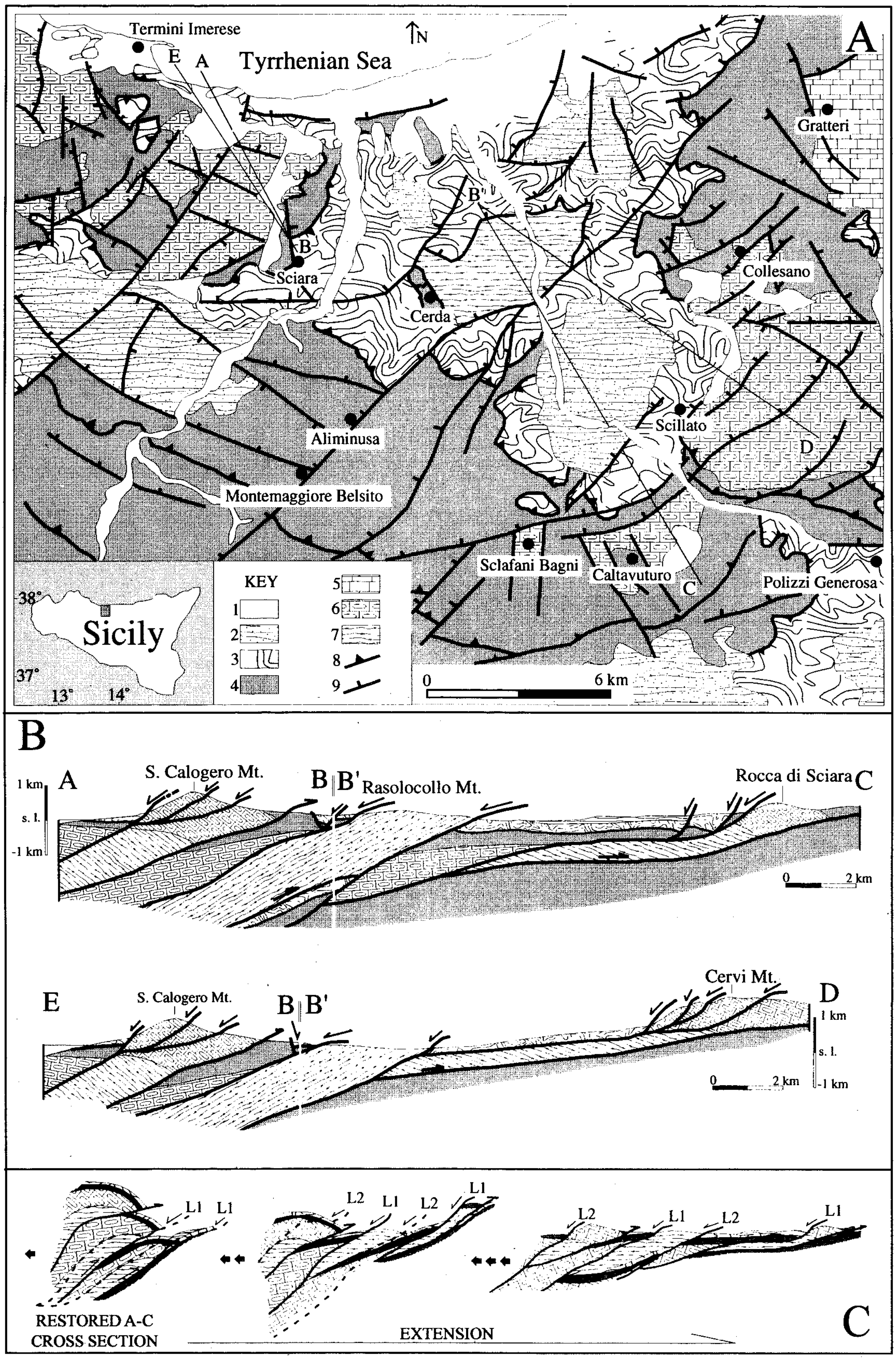

Fig. 11. **A.** Geological map and sections across the Madonie Mts. tectonic edifice, affected by neotectonic LANF systems. *1* – Pleistocene deposits; *2* – Tortonian–Pliocene sequences; *3* – Cretaceous–Paleogene Sicilidi terranes; *4* – Oligocene–Miocene Numidian Flysch; *5* – Mesozoic carbonates of Panormide Unit; *6* – Mesozoic carbonates of Imerese Unit; *7* – Triassic turbiditic sequences (Lercara Fm.); *8* – main thrusts; *9* – main extensional faults. **B.** Cross sections. **C.** Restored A–C cross section in which two main extensional events (L1 and L2) occurred during the Plio-Pleistocene. The key is the same for cross-sections

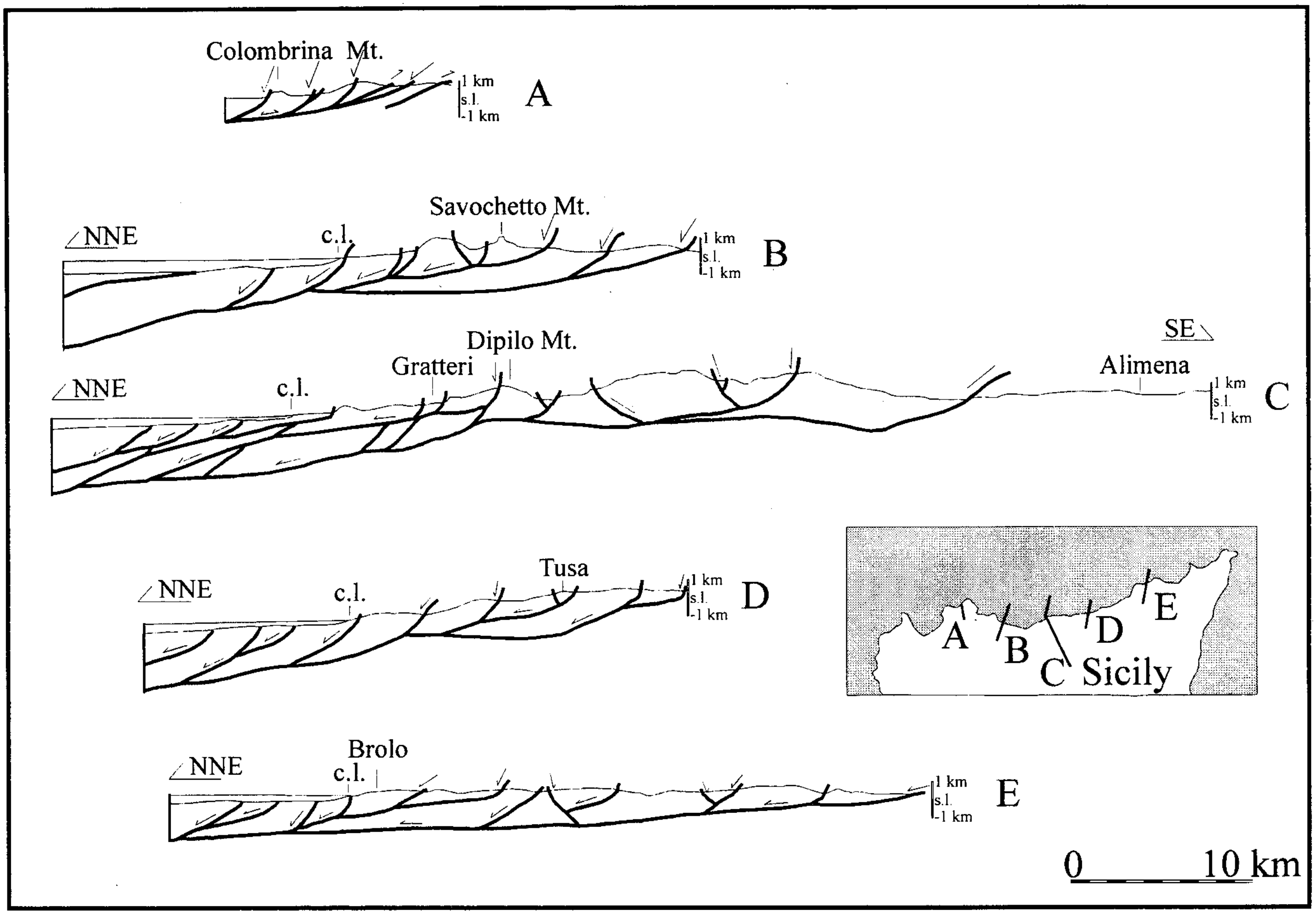

Fig. 12. Schematic structural sections across the Northern Sicily coastal area showing the presence of a recent low-angle (listric) normal fault systems cutting the E-W trending Sicily Belt

MARINE DATA OF THE SURROUNDING SICILIAN AREAS

Fig. 13 shows some examples of submerged neotectonic structures characterising the Sicily offshore areas, while the index besides (Fig. 14I) shows results of the assemblage of high-resolution seismic lines interpretation and geophysical and geological published data (Selli, 1974; Biju-Duval *et al.*, 1982; Argnani *et al.*, 1986; Makris *et al.*, 1986; Antonelli *et al.*, 1988; Argnani, 1987, 1990, 1993; Tricart *et al.*, 1990; Trincardi & Argnani, 1990; Catalano *et al.*, 1993a). The examples are from reinterpretation of published high-resolution seismic lines. From seismic interpretation, a Plio-Pleistocene clastic succession has been recognised, where stratal patterns and lateral terminations of the reflectors determine several depositional sequences. A number of depositional sequences are represented by groups of reflectors. They are characterised by seismic facies and stratal patterns that allow to the same trends that have been recognised in the Northwestern and Southern offshore Sicily by Agate *et al.* (1993), where seismics is controlled by well data. Thus, the age of boundaries between the groups of reflectors is correlated using sequence stratigraphy methods.

The seismic line 14A, from the Southern Sicily offshore areas, shows the NNE–SSW trending positive flower structures active since 1.4 Ma, involving the most recent sequences.

The seismic lines 14B and 14H, from the northwestern Sicily offshore areas, show the presence of an extensional tectonic event that started during the Messinian and produced a NW–SE regional-trending growth fault. The extensional (transtensional?) tectonic event persisted until the Early Pliocene and it was followed by inversion at 1.4 Ma, the result of which is today represented by the NW–SE trending strike-slip structures bounding the eastern side of S. Vito Peninsula.

Compressional tectonics during the Pliocene is recorded in seismic line 14C, where the N–S trending positive flower

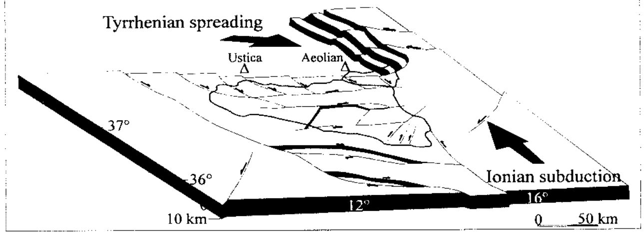

Fig. 13. Simplified 3D view of the Central Mediterranean with main hypothetical crustal features indicated. Large arrows indicate the direction of Tyrrhenian spreading and Ionian subduction. See text for explanation

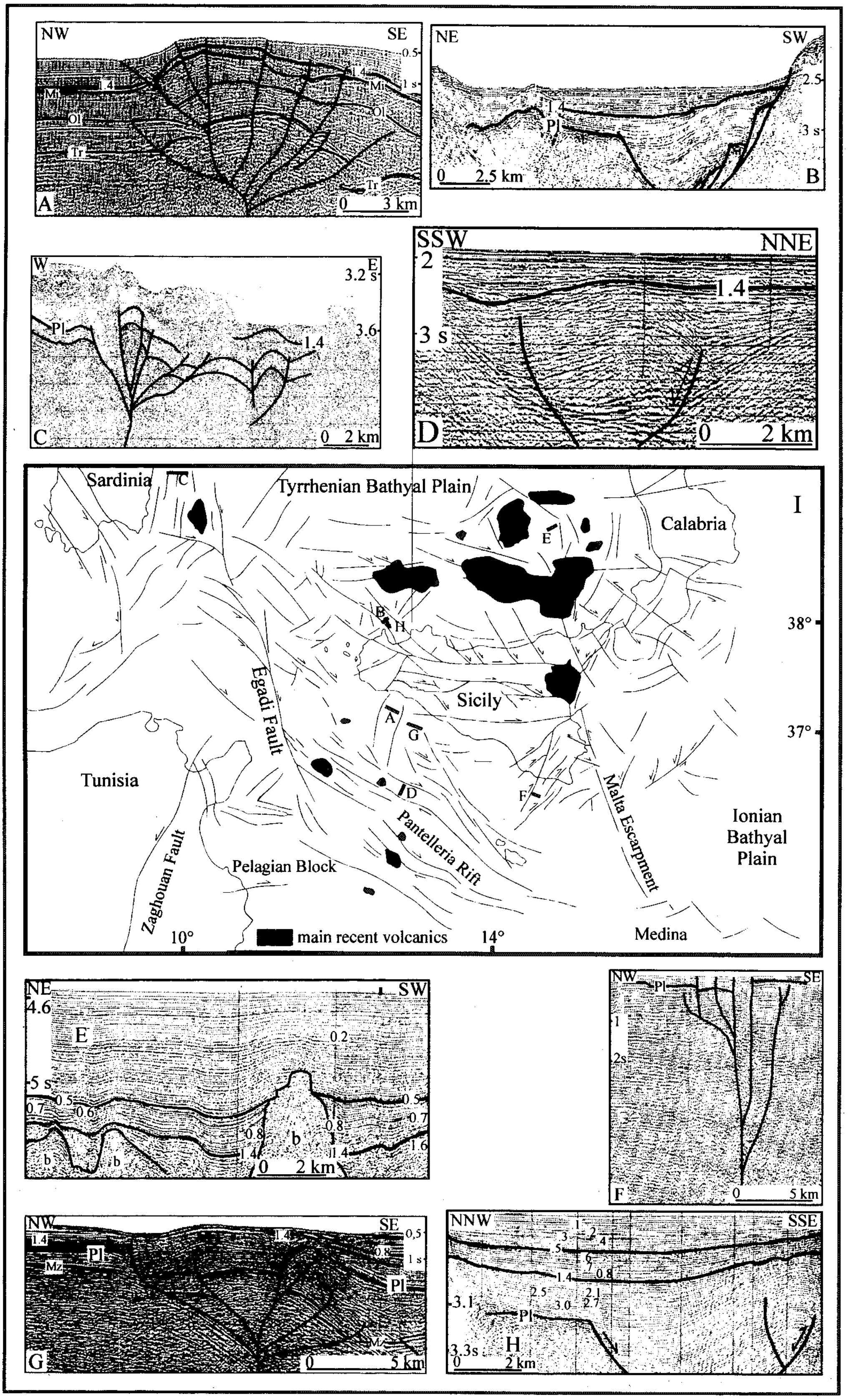

Fig. 14. A-H. Seismic lines from the Sicilian submerged surrounding areas. The ages of sequence boundaries are recognised on the basis of sequence stratigraphy methodologies and the comparison to the seismic facies of the profiles adjusted with the ODP sites. Tr – top of Triassic sequences; Mz – top of Mesozoic sequences; Ol – top of Oligocene sequences; Mi – top of Miocene sequences; Pl – bottom of Pliocene sequences. I – Index map in which main neotectonic features of the Central Mediterranean are represented. Lines represent the main dip- and strike-slip faults (indicated by arrows). See text for the interpretation of seismic lines

structures involve the deformation at least the sequences of 1.4 Ma in the Eastern Sardinia Shelf. Also, the seismic line 14D shows the presence of extensional tectonics during the Early Pliocene, followed by an inversion tectonic event active until 1.4 Ma, that produced the NW–SE trending structures in the Sicily Straits.

The seismic line 14E, from the Central Tyrrhenian, shows several angular unconformities bounding groups of reflectors. Particularly, in the depositional sequences bounded by the 1.4 and 0.8 isochrones, it is possible to assume the presence of extensional tectonics. The 1.4, 0.5 and probably the 0.2 sequence boundaries indicate compression. A very fast subsidence between 0.5 Ma and 0.2 Ma, and the intrusion of basaltic dikes, indicate extensional tectonic stages.

The seismic lines 14F and 14G, from the Hyblean submerged sector and the Gela Gulf respectively, show two NE–SW trending positive flower structures active since the Late Miocene, involving sedimentary sequences post- 1.4 Ma.

The above examples allow to synthesise the structural setting of the peri-Tyrrhenian submerged areas, often represented by transpressive and/or inversion geometries, synchronous with the "expansion" and "oceanization" of the central Tyrrhenian areas. Thus, the deformational phases recognisable in the submerged areas, as well as in the Sicily mainland, are alternatively expressed by transpressional and extensional tectonics. The age of deformations fits well to the deformational history as proposed by several authors (*e.g.* Agate *et al.*, 1993; Catalano *et al.*, 1993a, c):

- extension pre-4.8 Ma;
- compression until 3.0 Ma;
- extension between 3.0–2.4 Ma;
- inversion (transpression) between 2.4–1.4 Ma;
- extension between 1.4–0.8 Ma;
- compression at 0.8 Ma;
- extension after 0.5 Ma.

Is possible to recognise the overlap of extensional and compressional/transpressional tectonics that have produced several inversion geometries.

STRUCTURAL SUMMARY OF MARINE DATA

The main structural features of submerged areas surrounding Sicily, derive from an assemblage of published and unpublished seismic data. They include:

1) a western sector (between Sardinia, Egadi Islands and Tunisia) characterised by a prevalent NNW–SSE to NW–SE trending right-lateral transcurrent (locally transtensile) fault system ("*Egadi Fault*" of Finetti & Del Ben, 1986; and its northward prolongation), extending from the eastern Sardinia shelf to the Sicily Straits. The megariedels associated with this mega-structure determine several structural depressions (grabens and half-grabens) filled by Plio-Pleistocene sequences. Southwards, this faults system divides:

2) the Pelagian Block, where transpressive movements characterise the Eastern Tunisia (Zaghouan Fault), from:

3) the rhegmatic-like basins of the Pantelleria–Linosa area (Baumann & Reuther, 1985; Cello *et al.*, 1985a, b; Reuther & Eisbacher, 1985; Boccaletti *et al.*, 1987; Cello, 1987; Reuther, 1989). The Southern Sicily offshore is characterised by a rifting process (Pantelleria, Linosa) expressed by the NW–SE trending pull-apart basins, interpreted as the southeastward continuation of the Egadi Fault. The Southern Sicily offshore is also characterised by the NE–SW trending transpressive structures, interpreted as synthetic mega-riedels;

4) the Eastern Sicily offshore, characterised by a very important N–S trending structural line (Malta Escarpment) dividing the Hyblean–Malta–Medina Foreland (Illies, 1981; Cello *et al.*, 1984) from the Ionian subduction complex (Ionian microplate; Biju-Duval *et al.*, 1982);

5) the Northern Sicily offshore characterised by a mixing of extension and transpression processes during the late Plio-Pleistocene that determined several small basins and inversion structures (Tricart *et al.*, 1990);

6) the Tyrrhenian area *s.s.*, where the overall stretching and subsidence is coupled by the effects of the above described tectonic events.

SYNTHESIS OF THE REGIONAL STRUCTURAL SETTING

A review of deep geophysical data, deep well data, unpublished field survey data, seismic reflection profiles and published seismic data, makes it possible to distinguish the following tectonic domains for the Central Mediterranean:

1) The Southern Tyrrhenian Margin, characterised by NW–SE to E–W trending strong extension (represented on land by the E–W trending LANF systems) and a NW–SE trending right-lateral strike-slip displacements. Generally, the dip-slip system cuts the other one;

2) the Sicily mainland, characterised by:

a) the most external of the thrust complex (Sicanian and Gela Thrust Systems) emplaced from the Late Pliocene to the Pleistocene;

b) a prevalent E–W trending emergent and buried active right-lateral transcurrent faults with associated Riedel systems;

3) the Southern Sicily offshore, characterised by rifting processes;

4) the Eastern Sicily offshore, characterised by the active Ionian subduction complex.

The illustrated tectonic domains are consistent with the model shown in Figs. 15, 16 and 17B.

DISCUSSION

The recognised tectonic history in the submerged areas surrounding Sicily, and the comparison with deformational events in the mainland, indicate that the overall Tyrrhenian opening is characterised by several tectonic stages which are related to the time changes of regional stress field, as a result of geodynamic processes in the Mediterranean area. The change of stress field indicates that the driving forces ("mo-

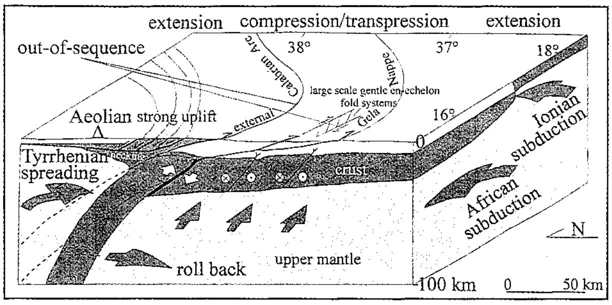

Fig. 15. Simplified 3D neotectonic crustal features of the Central Mediterranean. The picture shows the oblique movement of the African–Ionian plates compared to Tyrrhenian spreading and the main surface effects (crustal buried and/or emergent right-lateral transpressional faults, associated en-echelon fold systems and the main out-of-sequence thrusts), mostly related to the compressive stress induced in the subducted hinge zone of African plate by the "Tyrrhenian upper mantle". See text for explanation

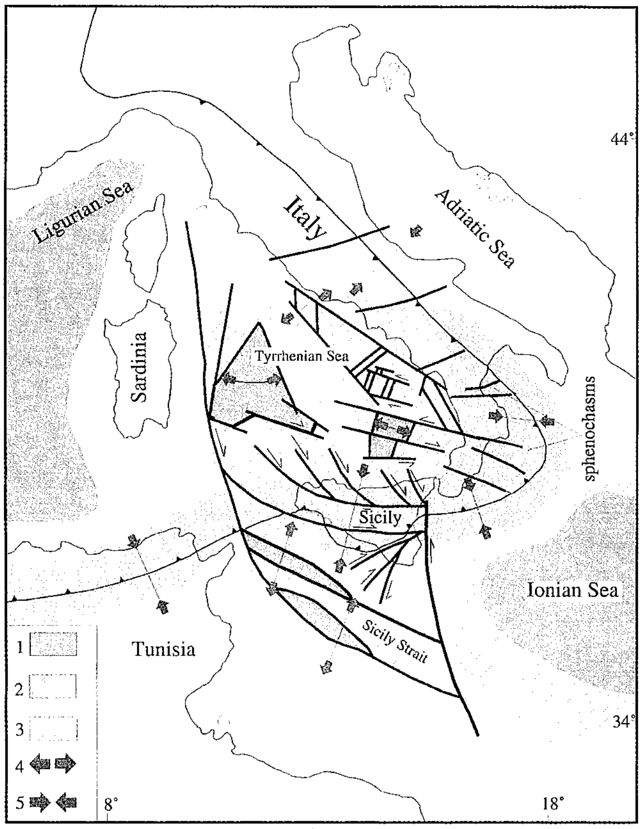

Fig. 16. Crustal structures of the Central Mediterranean related to neotectonic evolution. The sketch shows the present-day main structural features of the Tyrrhenian area, connected with rhegmatic-like mechanisms. According to this model, the Magnaghi–Vavilov area is interpreted as a sphenochasm basin which determines the easternmost transcurrent structures (e.g. Marsili and Paola Basins). See text for explanation. *1* – thinned and/or oceanic-type crust; *2* – Sicily–Apennine Thrust Belt; *3* – superimposed extensional areas; *4* – extension vectors; *5* – compression vectors

tors") can be a resultant of coupling of motion vectors that represent the northward movement of Africa and mantle processes. These "motors" are influenced by minor important factors, such as several structures resulting from older intraplate stresses and the Coriolis drift, and a geometric system characterised by plates moving on a sphere. The overall stretching of the Tyrrhenian area may be the result of complex, repeated tectonic stages, being the predominant effects of one of these main driving forces.

The recognised neotectonic lineaments in mainland Sicily, as well as in the surrounding submerged areas (Figs. 7, 8, 13 and 14), are interpreted in this paper as important crustal structures of the Central Mediterranean, being an expression of a regional shear system that controls the Tyrrhenian basin evolution. Thus, the trends of these structures and their regional patterns might be considered to be some of the main effects of the Tyrrhenian dynamics during the last few Ma. These effects (mostly represented by different scale shear zones) are now combined in a kinematic model of plate motion on a sphere affected by some mega-shear discontinuities. These discontinuities are related to the overall northward motion of Africa during the last Ma. The schematic structural setting presented in Figs. 13 and 16 summarises the main structural lineaments related to the geodynamic processes of the Tyrrhenian opening, reconstructed with the use of field observation in mainland Sicily discussed above and with the published and unpublished seismic data.

For a better understanding of the possible relations between the Tyrrhenian extension process and the coeval surrounding structures (extensional and/or compressional/transpressional as described before), the oblique convergence of the N–NNW Ionian subduction versus the SE Tyrrhenian spreading direction has also to be considered. This might induce strong extension in the central, as well as in peripheral basinal areas and create intraplate stresses with prevalently transpressional displacements in Sicily. A superimposed initial thermal input from the uppermost mantle to the lower crust may also be considered.

This model does not agree with the existing ones proposed for the Tyrrhenian–Apennine system kinematic evolution. These models involve:

a) Europe–Africa convergence, with lateral "extrusion" of some continental microplates (plastic-rigid deformation) and formation of oroclines (Tapponier, 1977; Boccaletti *et al.*, 1982);

b) Ionian–Adriatic passive subduction, with extension in the internal areas and compression in the external areas (Boccaletti & Guazzone, 1972; Malinverno & Ryan, 1986; Patacca & Scandone, 1990); and

c) Tyrrhenian extension as a consequence of gravitational collapse processes of a thickened lithosphere (Reutter *et al.*, 1980; Channel & Mareschal, 1989).

In the present author's opinion, the gravitational collapse processes alone (c-models) cannot produce the recognised rhegmatic basins configuration (Figs. 13 and 16). The Ionian–Adriatic passive subduction alone (b-models) may produce E–W trending shear systems (as in the a-type model of Boccaletti *et al.*, 1982), relatable to the Africa–Europe NNW–SSE convergence movement, but not a sphenochasm-like basin as in the present paper. Moreover, the initial thermal input and the asymmetric upper mantle "intrusion" are being subsequently controlled by shear zones resulting from a complicated and changing regional stress field. The temporal change of stress field, recorded in the poliphase-deformed Plio-Pleistocene sequences, suggests a rhythmical tectonics in the Central Mediterranean related to the resultant of group of vectors in the space that express forces (Fig. 17). In Fig. 17A a reference system is shown in which the velocity vectors that control the geodynamic evolution of Central Mediterranean are drawn. It is possible to decompose the velocity vectors as the resultants of African subduction–Egadi Fault movements (Va) and mantle uplift-Central Tyrrhenian opening (Vr). Besides, the African subduction rate is much lower with respect to the Egadi Fault rate, while the mantle uplift, as well as the Magnaghi–Vavilov basins opening, are considered to represent as angular velocities. The predominance in time of Va or Vr establish a compressional/transpressional or extensional tectonic regime respectively, in the Tyrrhenian and peri-Tyrrhenian areas (Fig. 17B).

Fig. 18A illustrates a possible kinematic evolution of a non-rigid plate moving on a sphere dissected by crustal shear discontinuities. Fig. 17B1 represents the initial setting, characterised by the N–S/NNE–SSW trending Apennine–Sicilian–Maghrebian mobile belt, and by several incipient mega-shear zones formed due to the northward Africa plate motion. The development of the initial stage is shown in Figs. 18B2 and 18B3, in which a progressive anticlockwise rotation and eastward shifting of the "Tyrrhenian microplate" producing extension and overlap areas is identified. In Figs. 18A and 18B the presence of the Ionian subduction complex has not been considered.

The main structural features in Fig. 18B3 are comparable with the observed structures in mainland Sicily and in the surrounding submerged areas (see also Figs. 13, 14 and 16).

In spite of the fact that the field observations and the geophysical data pertain to a relatively small area, it is possible to hypothesise the Tyrrhenian dynamics as caused by prevalent shear mechanisms, related to the Africa–Europe convergence and to examine boundary conditions that characterise the Central Mediterranean (the presence of a mobile belt, an active subduction complex, etc.). These conditions might have played a part in the dynamic development of the system.

Thus, the rhegmatic model proposed in this paper considers:

– the presence of a thickened African lithosphere below the more internal areas of the Sicily–Apennine Chain (Caputo *et al.*, 1972; Morelli *et al.*, 1975; Cassinis *et al.*, 1979; Scandone 1979, see Fig. 15);

– the crustal delamination (back-stop-like processes) occurrence, necessary to create the thickness of the subducted African lithosphere (Channel & Mareschal, 1989);

– the northward Neogene direction of the African plate (Dercourt *et al.*, 1986; Malinverno & Ryan, 1986; Dewey *et al.*, 1989);

– the Tortonian–Pleistocene roll-back of the African subducted slab (Malinverno & Ryan, 1986);

– the roll-back rate, which is higher than the African slab sinking rate.

This model also considers the oblique convergence vectors between the African–Ionian subduction complex and the Tyrrhenian opening during the late Pliocene–Pleistocene.

According to these conditions, it is likely that in the back area of the African–Europe collisional system, rhegmatic-like structures might have developed during the Plio-Pleistocene.

During the late Miocene–early Pliocene, the rhegmatic structures formed in the back area of the N–S trending thickened African–Europe suture, were the result of crustal pure-shear configuration.

In the early phase of Tyrrhenian stretching, a strong lower-crust thinning and heat input (upper mantle uplift) occurred. Viscous dissipation (low deviatoric stress) occurs where thermal anomaly takes place. In this stage, the extension in the upper crustal level started from an important right-lateral transcurrent crustal fault (Egadi Fault and its northward prolongation, Fig. 18B1). This crustal "lineament" bounds the Sardinia Block eastwards. Some mega-Riedels were also activated (*e.g.* the "Selli Line").

Activation of a low angle normal fault system cutting the upper (brittle) crustal level only might have facilitated subsidence of the proto-Tyrrhenian basin. The low stress domain widened with the expansion of the thermal anomaly, but the lower crust and upper mantle became stronger as the amplitude of the thermal anomaly has decreased.

The evolution of the "Selli Line" in a sphenochasm-like structure (eastward and/or south-eastward extension associated with the formation of oceanic-like crust in the Magnaghi and in the Vavilov Basins (Fig. 18B2) could be related to the northward motion of the African plate, producing at the same time an increasingly arched shape of the Sicilian–Apenninic suture zone, with clockwise rotations in Sicily (Fig. 18B3). The consequent asymmetric mantle uplift (Channel & Mareschal, 1989; model 4) is related to the asymmetric stretching.

In the following stage, a rapid lithospheric thinning could have been caused by convective thinning of the lithosphere, as a result of gravitational instability in the density contrast between the mantle, the lithosphere and the asthenosphere. Asymmetric mantle flow, and its south-eastward migration, might have induced a subcrustal compressive stress causing progressive verticalization of the previously subducted African plate and of the Ionian microplate (roll-back-like processes), consistent with geophysical and petrographic data from the Aeolian area (Barberi *et al.*, 1974; Wang *et al.*, 1989; Crisci *et al.*, 1991). The asymmetric upper mantle "intrusion" (Channel & Mareschal, 1989) might have "delaminated" the Wadati-Benioff surface toward the S–SE. In the hinge zone of the subducted plate, a strong stress could have produced a semi-brittle reverse crustal movement and a further contraction of the Sicily belt. This is even more likely as a zone of weakness was created by the previous African crust delamination related to the Miocene *back-stop* processes. The main effects of this contraction in mainland Sicily are also expressed by some out-of-sequence thrusting (Fig. 15) with major emplacement involving of the

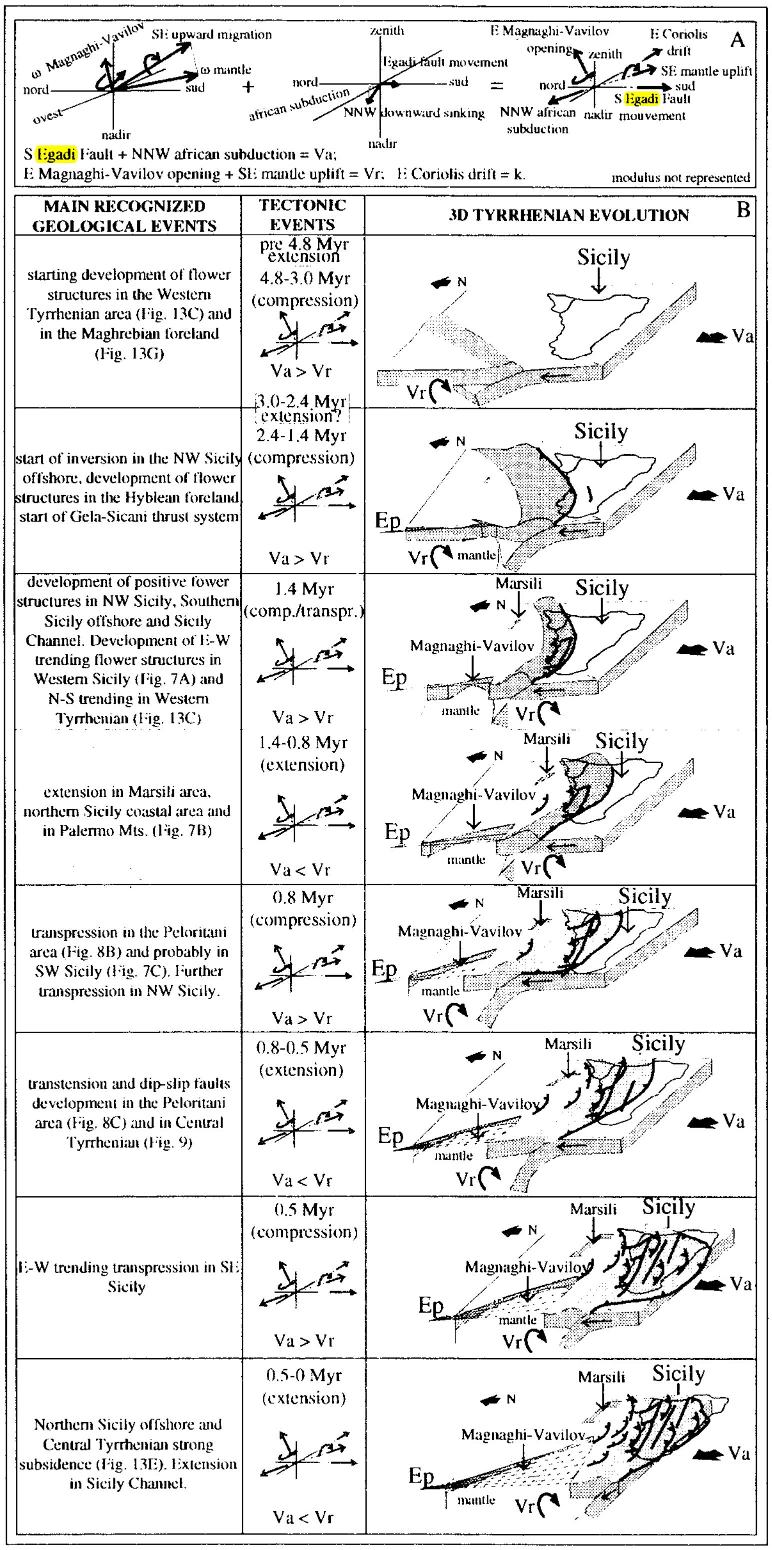

Fig. 17. **A.** Velocity vectors that controlled geodynamic evolution of the Central Mediterranean. It is possible to solve the velocity vectors as the resultants of African subduction-Egadi Fault movements (Va) and mantle uplift-Central Tyrrhenian opening (Vr). The African subduction rate is very low with respect to the Egadi Fault rate, while the mantle uplift, as well as the Magnaghi-Vavilov basins opening, are considered as angular velocities. **B.** Sequence of tectonic events related to the predominance in time of Va or Vr that established a compressional/transpressional or an extensional tectonic regime in the Tyrrhenian and peri-Tyrrhenian areas during the last 5 Ma. See text for explanations

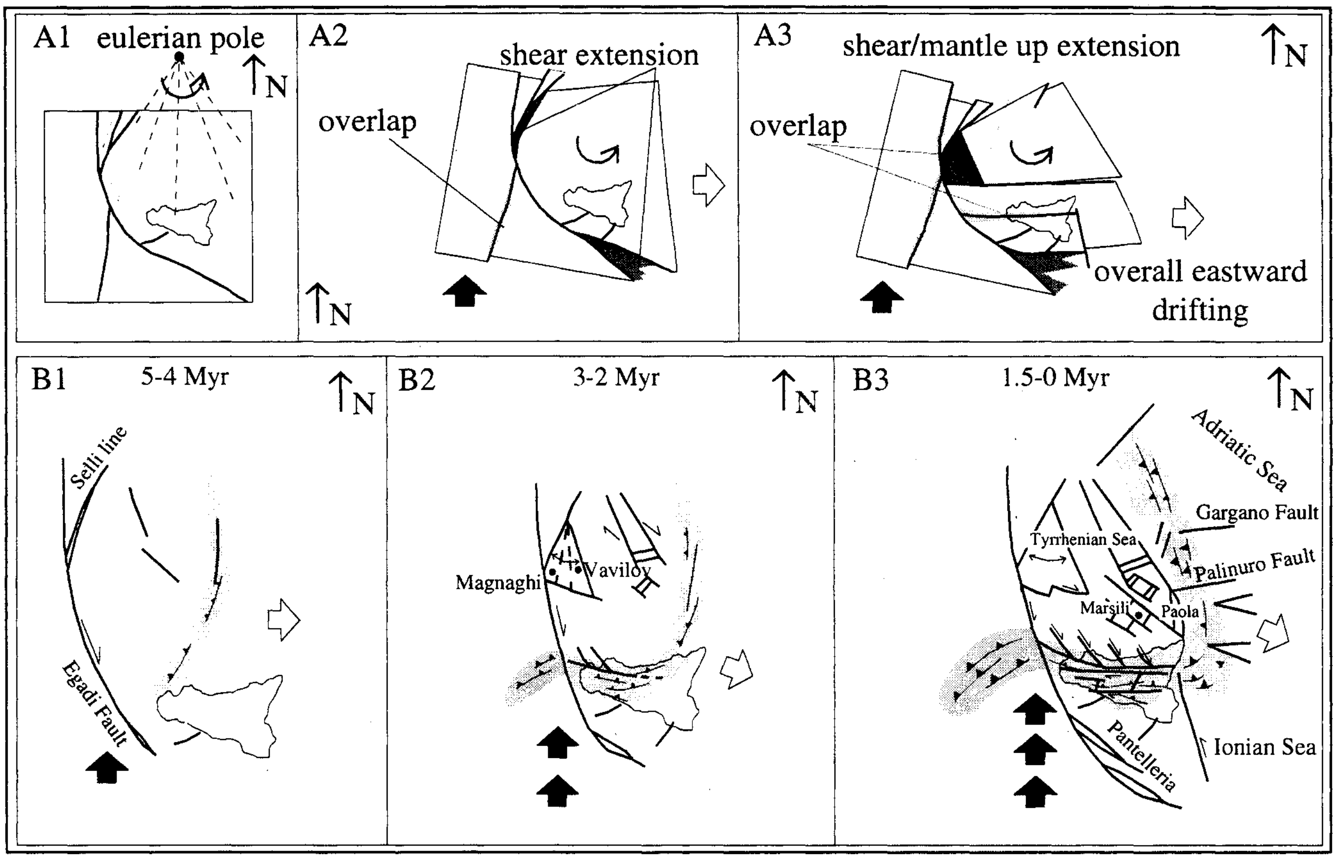

Fig. 18. **A.** Kinematic model of stretching due to mega-shear movements of blocks moving on a sphere. A1 is the initial stage. The progressive movement of the right part of the square induces a progressive rotation (scheme A2 and A3), with several overlapping and extensions areas. **B.** Hypothetical model of kinematic evolution of the Tyrrhenian area during the Plio-Pleistocene. During the Early Pliocene (scheme B1) in the back-area of the N-S trending half-arched Sicilian–Apenninic suture zone an important right-hand transcurrent crustal fault (Egadi Fault and its northward prolongation) bounds eastward the Sardinia Block. Some mega-riedels were activated during this stage (*e.g.* the Selli Line), when an overall extensional status characterised the proto-Tyrrhenian area. The northward prosecution of the African "advancement" (scheme B2) produced a progressively more and more arched shape of the suture zone and the evolution of the Selli structural line in a sphenochasm-like structure. The prosecution of the African plate motion (scheme B3) accentuates the overall E-W and/or NW-SE trending extension of the Tyrrhenian area and supports the eastward formation of further rhegmatic-like basins (e.g. the Marsili Basin). There are E-W trending transpressional structures, with associated NW-SE Riedel systems, cutting the Northern Sicilian Belt progressively toward the east. The progressive flexural loading of the Sicilian Belt, together with the right-hand motion of the "Egadi Fault" in the Pelagian area, contributes to the southern crustal thinning and rifting processes in the Pantelleria rhegmatic-like basin

Sicanian–Gela Thrust Systems and the External Calabrian Arc (Figs. 3 and 10).

The very strong uplift of the Northern Sicilian Belt during the last 2–3 Ma, and the activation of the northern Sicily LANFs system (see Fig. 12), could be explained by the presence of a deep (intermediate?) necking level below the northern side of the Sicily shelf (Fig. 15). The intraplate stresses related to the northward motion of the Africa plate, and to the Tyrrhenian mantle uplift (and as a result of oblique convergence of the Tyrrhenian–Ionian complexes) in the Sicilian Belt, might have activated the recognised E–W trending right-lateral crustal transpressive fault systems (Figs. 7A, 7C, 7D, 8D and 8E) and, progressively towards the east, the associated NW–SE trending megariedel system (Figs. 7C, 8A and 8B, see also Figs. 13 and 14).

The prosecution of the African plate motion accentuated the overall E–W and/or NW–SE trending extension of the Tyrrhenian area. It supported the eastward formation of further rhegmatic-like basins (*e.g.* the Marsili Basin, Fig. 17) and other small sphenochasms over the very arched areas of the subduction complex (Calabrian Arc, Fig. 18B3), with a clockwise rotation of the Maghrebian terrains in Sicily (Channel *et al.*, 1980); and widespread NNE–SSW and E–W trending deep structures in the Apennines (Lavecchia *et al.*, 1984). The asociated progressive flexural loading of the Sicilian Belt, due to the out-of-sequence "Gela Thrust System", together with the effects of the overall right-hand motion of the "Egadi Fault" in the Pelagian area, probably contributed to the southern crustal thinning and rifting processes in the Pantelleria rhegmatic-like basin (Carbone *et al.*, 1982; Grasso & Reuther, 1988; Grasso *et al.*, 1990).

CONCLUSIONS

It was possible to propose a crustal model and to reconstruct kinematic history of the Tyrrhenian Basin and surrounding areas on the basis of field analysis of some neotectonic structures outcropping in Sicily, mapping the main neotectonic features from published and unpublished seismic data, with the aid of the existing deep geophysical data, and on an analysis of the literature.

The recognised neotectonic structures in mainland Sicily appear, as a whole, to represent a shallow expression of deep-seated dextral strike-slip systems affecting the Sicilian Maghrebides. This system can be linked with the submerged mega-structures characterising surrounding areas, that often are represented by regional trending positive flower structures. The proposed model is thus based on a rhegmatic shaping of the regional neotectonic evolution of the Central Mediterranean.

The sequence of neotectonic events observed and previously described in mainland Sicily, as well as that recognised through the seismic interpretations, appear to be the result of a "pulsating" tectonics. Compressional tectonics is prevalently represented by positive flower structures and large out-of-sequence thrusting in the peri-Tyrrhenian areas, while extensional tectonics is represented by rhegmatic-like basins formation.

In the present paper, the Tyrrhenian opening is related to the northward movement of the African plate during the Neogene, the presence of thickened lithosphere characterising the Southern Apennines–Sicilian Belt, and the Tortonian–Pleistocene roll-back of the African subducted slab. This model takes also into account the fact that roll-back rate is higher than the African slab sinking rate and the oblique convergence vectors between the African–Ionian subduction complex and the Tyrrhenian opening during the late Pliocene–Pleistocene.

The regional N–S trend of the maximum compressional axis related to the African motion is compensated for by an extension toward the E–SE of the Tyrrhenian basin which in the Magnaghi–Vavilov areas has a sphenochasm-like geometry.

The neotectonic history recorded in outcropping rock sequences and submerged areas (especially in Sicily and in its northern offshore) reveals that different synchronous tectonic events in the Central Mediterranean might be in part related to Tyrrhenian extension and African–Ionian subduction velocity vectors, even if the development of system appears have also been controlled by regional-trending shear zones, probably activated during the tardy collisional processes of the Alpine Belt.

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Streszczenie

WYDARZENIA NEOTEKTONICZNE I KINEMATYKA BASENÓW TYPU REGMATYCZNEGO NA SYCYLII I PRZYLEGŁYCH OBSZARACH. IMPLIKACJE DO STRUKTURALNEGO MODELU OTWIERANIA SIĘ MORZA TYRREŃSKIEGO

Fabrizio Nigro

Otwieranie się Morza Tyrreńskiego jest związane z ruchem Afryki ku północy w czasie neogenu, obecnością zgrubiałej litosfery charakterystycznej dla pasa Południowe Apeniny–Sycylia, i tortońsko-plejstoceńskiego cofnięcia się zanurzonej części płyty afrykańskiej. Przedstawiony model bierze również pod uwagę fakt, że w późnym pliocenie–plejstocenie, tempo cofania się płyty afrykańskiej było większe niż tempo jej subdukcji i skośnej konwergencji między afrykańsko-jońskim kompleksem subdukcyjnym oraz otwierania się Morza Tyrreńskiego.

Południkowy kierunek osi maksymalnej kompresji związany z ruchem Afryki jest skompensowany przez rozciąganie w kierunku E–SE basenu tyrreńskiego, który w rejonie Magnaghi–Vavilov miał geometrię sfenochasmiczną.

Neotektoniczna historia zapisana w odsłonięciach i na obszarach zatopionych (szczególnie na Sycylii i na północ od niej) wskazuje, że różne synchroniczne wydarzenia tektoniczne w centralnej części Morza Śródziemnego mogą być częściowo rezultatem szybkości rozrostu Morza Tyrreńskiego i subdukcji afrykańsko-jońskiej, nawet jeśli rozwój systemu był również kontrolowany przez regionalne strefy ścięć, które prawdopodobnie zostały zaktywizowane w końcowej fazie procesów kolizyjnych w łuku Alp.