Volcanism in the Campania Plain:
Vesuvius, Campi Flegrei and Ignimbrites
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Chapter 2

The Pleistocene extension of the Campania Plain in the framework of the southern Tyrrhenian tectonic evolution: morphotectonic analysis, kinematic model and implications for volcanism

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ABSTRACT

The Tyrrhenian margin of the Apennine chain (TMAC) experienced widespread extensional tectonics characterized by volcanism and the formation of several marine and intermontane troughs and basins in Pleistocene times. The Campania Plain is part of this extensional system, which encompasses an area from southern Tuscany to the northern margin of Calabria. Extensional tectonics affecting these continental areas is likely to be related with the final stages of the opening of the southern Tyrrhenian Sea, which developed since Middle Tortonian times. This work presents a quantitative kinematic model explaining the relationships between extension in the Tyrrhenian Sea, basin formation in the TMAC, migration of the Apenninic arcs and geotectonic setting of the volcanism. A synthesis of the volcanic, structural and geophysical data available in the literature, coupled with a detailed morphotectonic analysis of the study areas were used in computer-aided reconstruction techniques based on interactive modelling of rigid block rotations to realistically assemble in a unique kinematic framework the first-order structures that are observed in the Apennines area and in the Tyrrhenian basin.

Once established, the extension directions in the various sectors of the Apennine chain, by comparing the results of the morpho-structural analysis with data collected from the abundant geological literature, we identified two distinct kinematic elements characterizing the Apennine chain that, from Plio-Pleistocene times, moved independently with respect to the Eurasian reference plate: the Northern Apennines Arc (NAA) and the Southern Apennines Arc (SAA). On the basis of the first-order geological and geophysical constraints, as well as on trial and error experiments, we identified two distinct rotation stages for the Apennine chain. During the first stage, from 3.5 to 0.78 Ma, the NAA and the SAA migrated independently. In the second stage, from 0.78 Ma to the present, the NAA stopped migrating, while the SAA continued migrating towards SE. Thus, N-S extension in the Campania Plain is the result of the relative motion of the NAA with respect to the SAA during the first stage only, whereas the present-day NW-SE extension in this area, which is characterized by intense volcanism (e.g. Ignimbrites, Somma-Vesuvio, Ischia, Campi Flegrei), is related to the migration towards the SE of the SAA with respect to the NAA.

The simplifying assumption of rigidity of the two arcs does not substantially affect the model presented, which only aims at describing the process of extension and associated magmatic activity in the TMAC. Furthermore, the model presented above could not take into account many aspects of the complex tectonic evolution of the TMCA. Nevertheless, it realistically assembles in a unique kinematic framework the first-order structures that are observed in the Apennine area and in the Tyrrhenian basin.

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1. Introduction

Large-scale extensional tectonics coupled with orogenic processes is a typical feature of the Miocene to the recent peri-Tyrrhenian orogenic belt of Italy and Sicily. In central-southern Italy, while the thrust belt-foredeep system of the Apennine chain continued migrating towards the present-day Adriatic–Ionian foreland (Patacca et al., 1990), the Tyrrhenian margin of the Apennine chain (TMAC) experienced widespread extensional tectonics characterized by volcanism and the formation of several marine and intermontane troughs and basins in Pleistocene times. The Campania Plain, an E-W elongated basin infilled by up to 3000 m of Pleistocene volcaniclastic and alluvial sediments (Milia and Torrente, 1999), is part of this extensional system, which encompasses an area extending from southern Tuscany to the northern margin of Calabria (Fig. 1).

Extensional tectonics affecting these continental areas is likely to be related with the final stages of opening of the southern Tyrrhenian Sea (STS). The Tyrrhenian Sea, which developed since Middle Tortonian times, is the youngest basin of the western Mediterranean (Sartori et al., 2004) and, since the 1960, it has been subject to several geological and geophysical explorations and surveys. In spite of the huge amount of available data, the geodynamic evolution of the Tyrrhenian basin and surrounding regions are yet to be coherently described and have been subject to controversial interpretations (Biju-Duval et al., 1977; Dercourt et al., 1986; Malinverno and Ryan, 1986; Dewey et al., 1989; Boccaletti et al., 1990; Carmignani et al., 1995; Lavecchia et al., 1995; Faccenna et al., 1996; Ferranti et al., 1996; Turco and Zuppetta, 1998; Jolivet and Faccenna, 2000; Faccenna et al., 2001; Rosenbaum et al., 2002; Lavecchia et al., 2003; Peccerillo and Turco, 2004). In particular, the kinematic relationships between extension in the Tyrrhenian Sea, basin formation in the TMAC, migration of the Apenninic arcs and geotectonic setting of volcanism still remain to be determined.

In order to reconstruct the tectonic evolution of the Campania Plain during the Pleistocene, in the framework of the southern Tyrrhenian tectonic history, we tried to outline the relationship between extensional tectonics and volcanism that characterized the TMAC during the last 3.5 Myrs. We used volcanic, structural, geophysical and morphological data available in the literature, as well as computer-aided reconstruction techniques based on interactive modelling of rigid block movement.

2. Geology of the Tyrrhenian–Apennines region

In this section, we briefly discuss the main structural and geological features of the Apennine chain and the Tyrrhenian basin.

2.1. *The Apennine chain*

The Apennine–Maghreb chain is a Neogene thrust belt which comprises Mesozoic to Palaeogene sedimentary rocks, derived from different basins and shelf paleogeographic domains located in the Adria continental margin of the African plate (Patacca et al., 1990).

The formation of the thrust belt started with the collision between the European Corsica–Sardinia block and the Adriatic–African margin, an event that in Oligocene times led to the closure of a tract of the Neo-Tethyan ocean (Dewey et al., 1989). In fact, in Liguria, Toscana and Calabria, Mesozoic to Cenozoic metasedimentary and ophiolitic rocks, the remnants of an ancient accretionary wedge (Knott, 1994), overrode Apenninic Mesozoic carbonate rocks that belonged to the Adriatic domain. In Calabria and NE Sicily, Palaeozoic igneous and metamorphic rocks with the overlying Mesozoic to Cenozoic sedimentary cover, which are considered to be a fragment of the European margin of the Neo-Tethys (Kastens and Mascle, 1990; Knott, 1994 and references therein), overrode the ophiolitic complex.

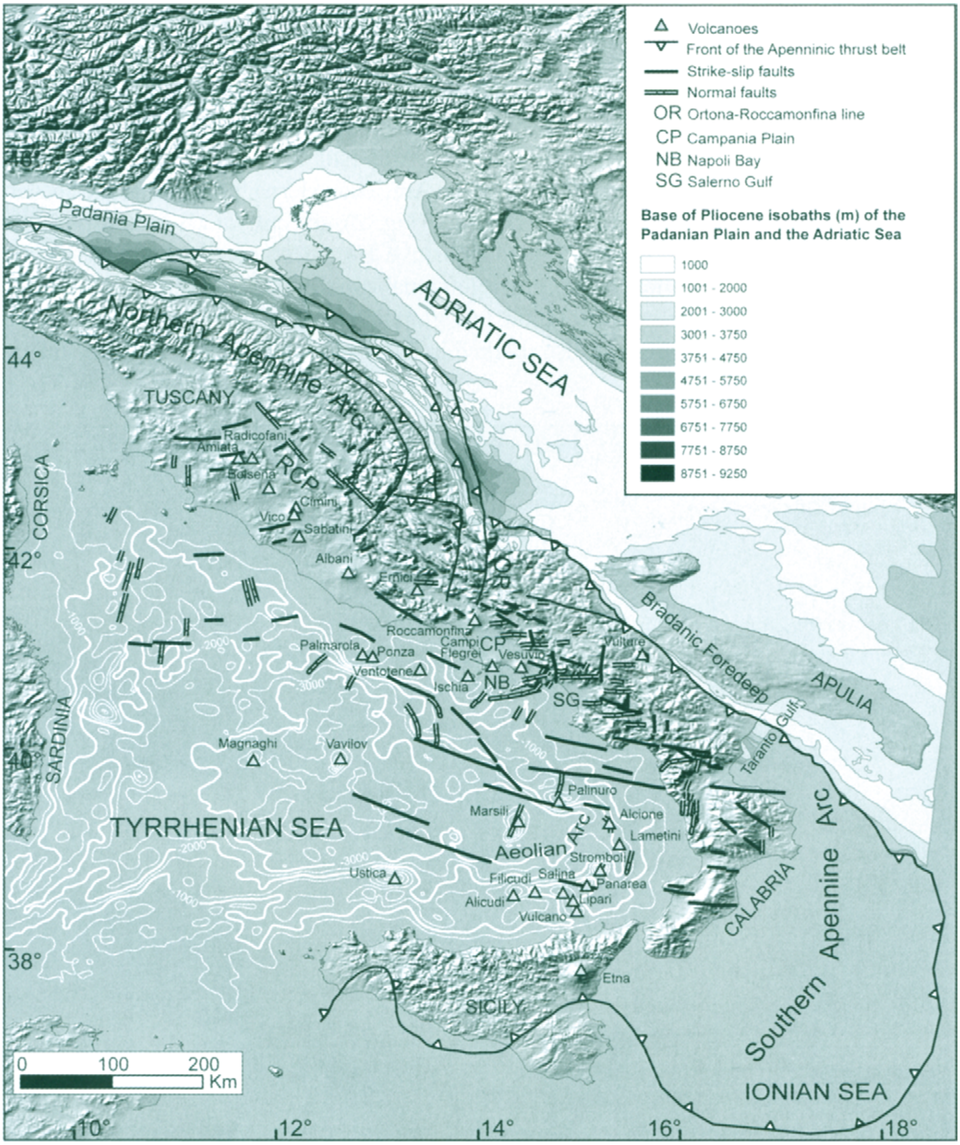

Figure 1. Structural sketch of the Tyrrhenian Sea and the Apennines.

Therefore, since the Early Miocene a collisional belt separated the Corsica–Sardinia European (Eurasian) block from the undeformed Adria domains (Patacca et al., 1990).

From a structural point of view, Patacca et al. (1990) distinguished two major arcs in the Apennine chain: the NE-verging Northern Apennines Arc (NAA), which extends from Monferrato to Molise, and the E and SE-verging Southern Apennines Arc (SAA), which extends through the Calabrian arc from Molise to Sicily (Fig. 1). The two arcs merge along a transversal lineament known as the "Ortona–Roccamonfina line" (Locardi, 1982; Patacca et al., 1990). According to these authors this lineament represents a Late Pliocene dextral strike-slip fault. A third minor arc is located between the two major arcs in the Molise area, but its origin is still unclear. The foreland of these arcs is represented by the Ionian–Adriatic domain.

The Adriatic foreland flexure is regionally drawn by the SW deepening base of Pliocene isobaths (Royden et al., 1987; Bigi et al., 1990), a feature that is particularly evident in the NAA (Fig. 1). In the STS, deep earthquakes foci (Anderson and Jackson, 1987) draw the Ionian lithosphere subducted under the Calabrian Arc. The external portions of the arcs are marked by negative Bouguer gravity anomalies (Fig. 2), except for an area around the Vulture volcano where the Apulia foreland positive Bouguer anomalies cut across the Bradanic foredeep to join the positive gravity anomalies in the STS. In this area, the positive gravity anomaly corresponds to a low topographic relief of the Apenninic thrust belt (Fig. 2). These crustal features are also marked by a high-velocity crustal body at shallow

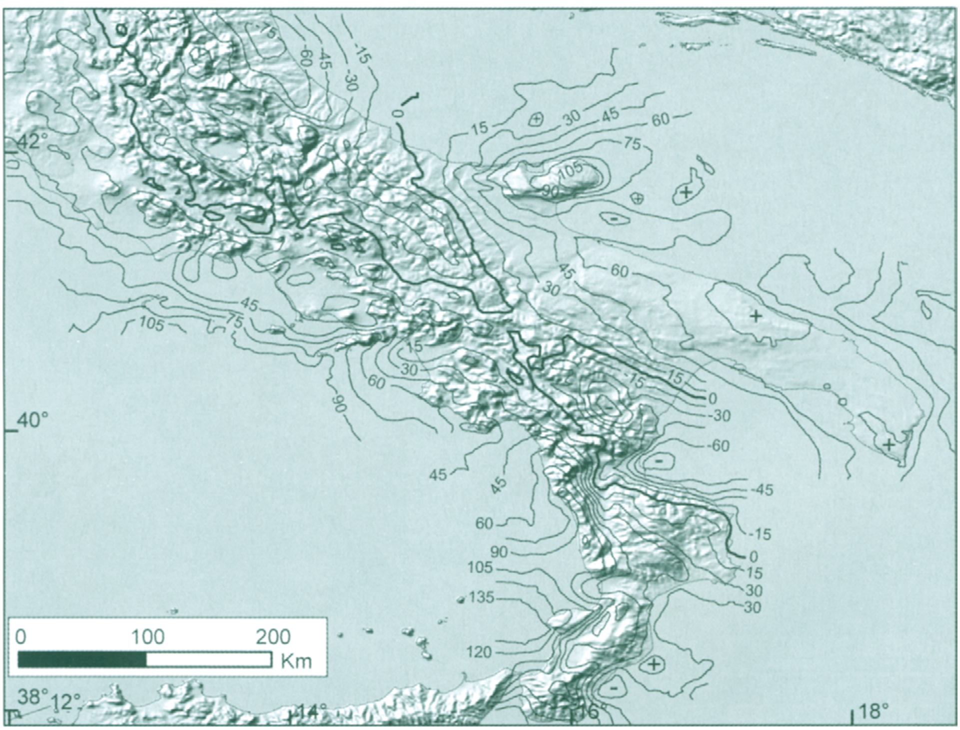

Figure 2. Gravity map of central-southern Apennines. Bouguer isoanomalies in mGal.

depth as shown by 3D crustal P-wave tomography (Alessandrini et al., 1995). Westward, the Apenninic domain boundary is represented by the Tyrrhenian margin. This boundary is marked by a volcanic alignment that span from southern Tuscany to the Aeolian Islands arc. Along the northern sector of this margin (from southern Tuscany to Campania), high-K volcanoes that have been dated from the Late Pleistocene to the present (Serri et al., 2001 and references therein) occur. The apparatuses of these volcanoes follow significant structural alignments. In particular, in the Latium–Tuscany area they are NW-SE aligned, whereas in Campania they follow an E-W trend. The southern tract of the boundary (from Bay of Naples to the Eolian Islands) comprises calc-alkaline volcanoes (Peccerillo and Turco, 2004 and references therein).

2.2. The Tyrrhenian basin

Starting from Late Tortonian times, severe extensional processes took place along the western side of the Apennine chain, with extensive rifting and rapid tectonic subsidence (Kastens et al., 1988 and references therein). Extension in the Tyrrhenian region and compression in the Apennine chain coexisted with a progressive migration of the rift-thrust belt-foredeep system towards the present-day Po Plain–Adriatic–Ionian foreland (Ricci Lucchi, 1986; Patacca et al., 1990; Cipollari and Cosentino, 1992). Marine conditions were reached in the western part of the Tyrrhenian basin in early Messinian times (Sartori et al., 2004). From Early Pliocene times, a significant volcanic activity was associated with rifting processes, leading to the onset of high-K magmatism in the Tyrrhenian continental margin of the Italian peninsula (Beccaluva et al., 1990, Peccerillo and Turco, 2004).

Trincardi and Zitellini (1987) pointed out the strong asymmetry of conjugate rifted margins in the STS, represented respectively by the eastern Sardinia continental margin and by the central southern Italy. According to these authors, in the Tyrrhenian margin of Campania the asymmetric rifting process could have been controlled by an east-dipping low-angle crustal detachment fault.

In this view, the lower plate of the detachment system is represented by the Sardinian passive margin, while the upper-plate counterpart is the Campanian margin.

The existence of oceanic crust in the STS is likely to be restricted in the Vavilov basin and in the Marsili basin (Marani, 2004; Sartori et al., 2004). Nevertheless, there is evidence of a large area encompassing the Magnaghi and Vavilov seamounts that shows an oceanic-like Moho depth of about 10 km (Carrara, 2002) (Fig. 3). An E-W seismic section across the Magnaghi and Vavilov seamounts reveals the absence of lower crust and the presence of tilted upper crust blocks (Sartori et al., 2004). Furthermore, seismic velocities recorded along the same section suggest the occurrence of a wide continent–ocean transition characterized by sub-continental serpentinized mantle (DSDP Leg 107, site 651; Kastens et al., 1988).

3. Morpho-structural analysis

In order to analyse the major structural and tectonic features characterizing the TMAC, we applied a technique based on the interpretation and synthesis of different types of

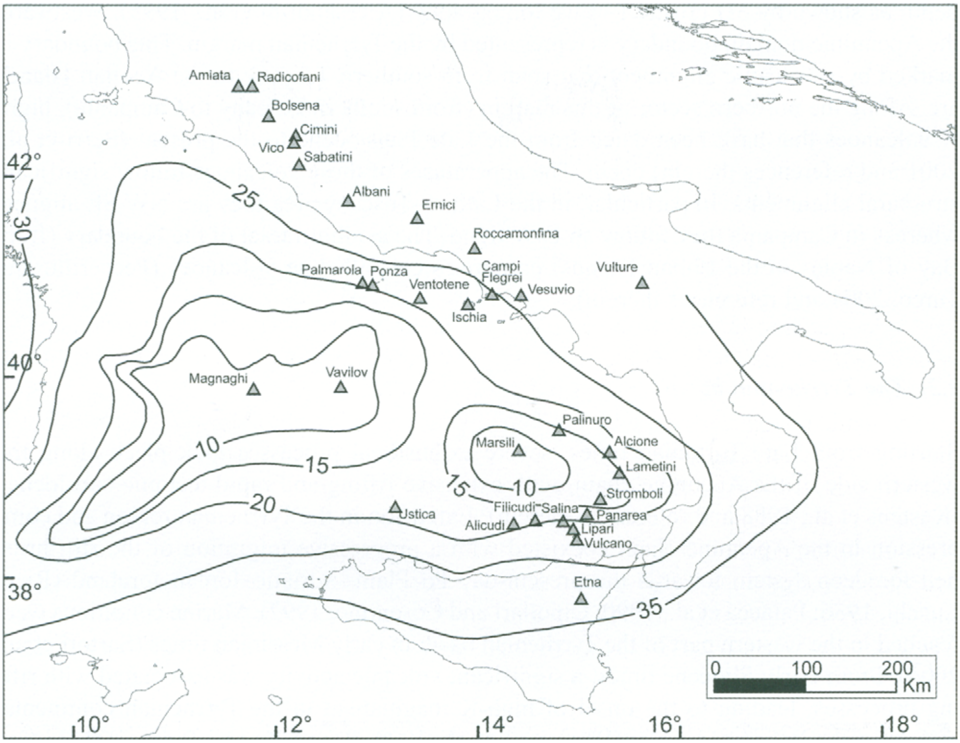

Figure 3. Schematic map of the Moho depths (in km) in the Tyrrhenian-Apennines system (after Carrara, 2002).

remote sensing data in the light of the geological and geophysical data published in the literature. Landsat ETM 7 and Shuttle Radar Topography Mission (SRTM) elevation data (ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/) constituted the remote sensing data set. The Landsat ETM 7 imagery has a 30 m pixel resolution and contains seven spectral bands. Bands 1–5 and 7 contain spectral information, while band 6 contains thermal information. In this study, we choose the 7:4:2 band combination, which satisfactorily highlights the geological information. These imageries were combined with an SRTM imagery covering the same area. This SRTM image has been processed into a Digital Elevation Model (DEM) with a resolution of 90 m. The Geologic Map of Italy from Servizio Geologico d'Italia (scale 1/1,250,000) (Compagnoni and Galluzzo, 2004) and the Structural Model of Italy (scale 1/500,000) (Bigi et al., 1990) were used to insert field geological data and guide the remote sensing interpretation. The Gravity Map of Italy (Carozzo et al., 1992) and CROP-MARE (Scrocca et al., 2003) seismic data were used to further constrain the interpretations. Recently, the Institute of Marine Science (ISMAR) of the National Research Council (CNR) carried out a high-resolution bathymetric survey (Marani and Gamberi, 2004) that we combined with land topographic data to produce a high-resolution image of the in-land and sea-bottom morphology of the Italian peninsula and the Tyrrhenian Sea (Figs. 4–6). This combined map allowed us to perform the identification of tectonic features and lineaments on a large region that encompasses both on-land and marine areas.

3.1. The morpho-structures of the Apennine arcs

In the NAA, the main structural lineaments clustered into principal sets striking NW-SE and NE-SW (Fig. 4). The NW-SE trending set – that characterize the Umbria region, southern Tuscany and part of the Lazio region – shows many morphological markers, with evidence of structural highs and lows. Many authors (e.g. Deiana and Pialli, 1994; Calamita and Deiana, 1995) interpreted these structures as dip-slip normal faults, known as "faglie appenniniche" (i.e. Apennine-trending faults), related to block-faulting (Sani et al., 1998) controlling the formation of Mio-Pliocene basins.

The NE-SW striking structures, known as "faglie anti-appenniniche" (i.e. anti-Apennine-trending faults), have been interpreted as transfer faults related to the NW-SE trending extensional faults (Bartole, 1995). The evidence of small pull-apart basins formed along these lineaments supports this hypothesis (Bonini, 1997).

The structural pattern of the SAA is much more complex and at least five sets of lineaments can be identified (Fig. 5). The first set strikes N110-N120 and propagates throughout the southern Apennines from the Salerno Gulf to the Taranto Gulf and the Ionian foredeep (Fig. 5). These lineaments seem to be superimposed over a second set of N140-N150 striking lineaments. According to previous interpretations (Turco et al., 1990; Knott and Turco, 1991) both these sets of lineaments are interpreted as left-lateral strike-slip faults. Sharp escarpments mark a third set of NE-SW anti-Apenninic-striking structures (Fig. 5), which have been interpreted as normal faults (Knott and Turco, 1991; Milia and

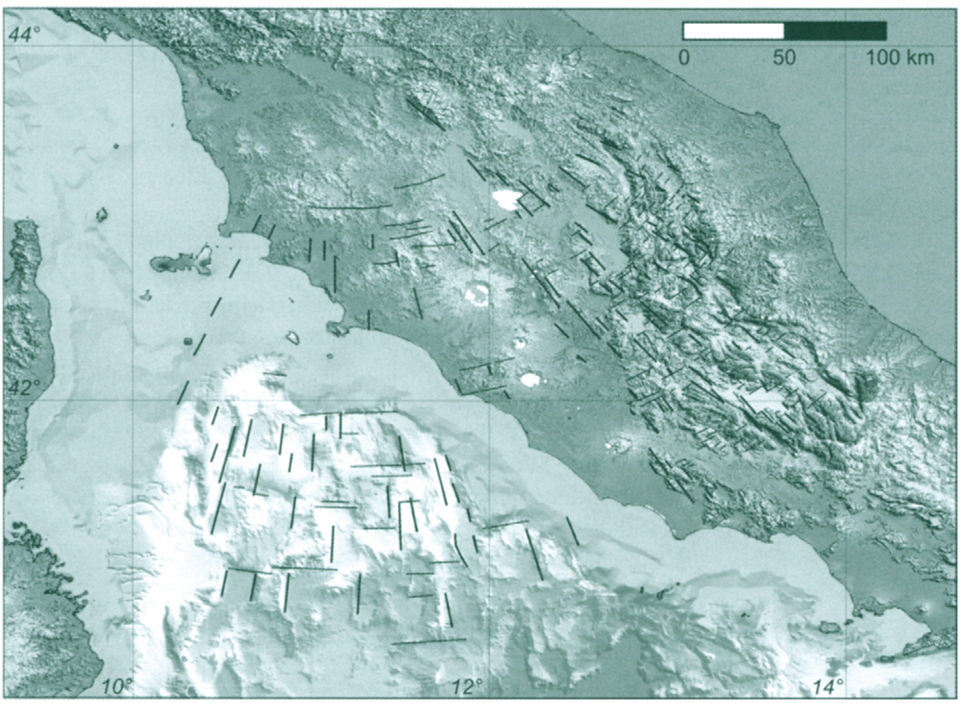

Figure 4. Tectonic lineaments in the northern Apennine Arc and in the central-northern Tyrrhenian Sea detected from remote sensing data and bathymetric data interpretation.

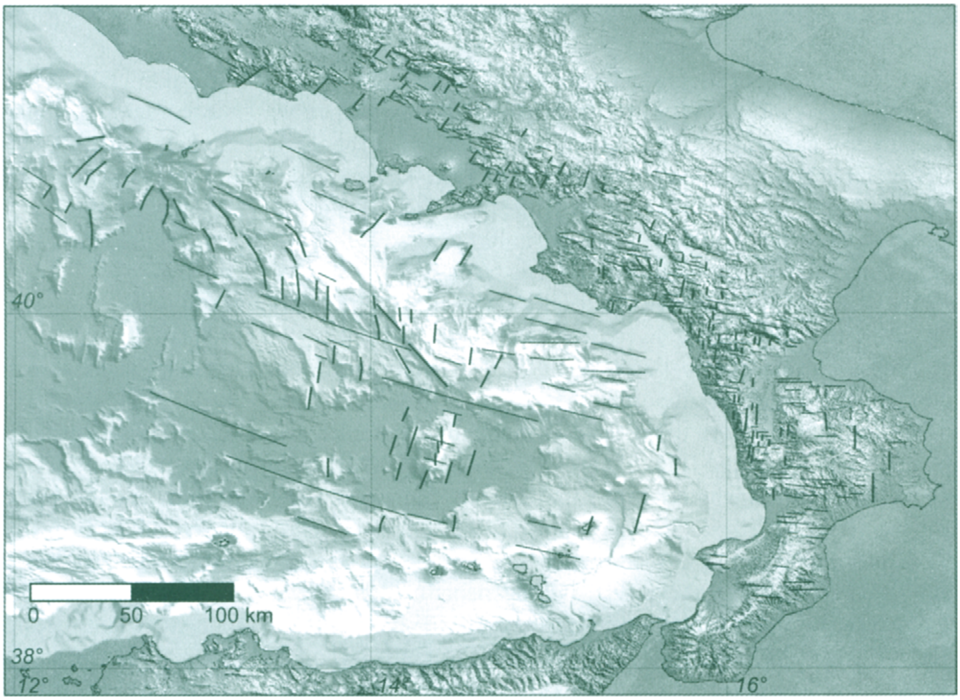

Figure 5. Tectonic lineaments in the southern Apennine Arc and in the southern Tyrrhenian Sea detected from remote sensing data and bathymetric data interpretation.

Torrente, 1999, 2000). It should be noted that in the NAA the anti-Apenninic structures are mainly strike-slip faults, whereas in the SAA they generally have an extensional kinematics. This supports a first-order sub-division of the Apennine chain into at least two main arcs on the basis of homogeneous structural patterns.

Finally, a double set of E-W and N-S trending lineaments characterizes the Irpinia area, from southern Latium and Abruzzi regions to the Monte Vulture volcanic apparatus (Fig. 6). The E-W trending lineaments are in some cases associated with basins infilled by lacustrine sediments. Examples of such basins are the Isernia and Boiano basins (Bosi et al., 2004) and the Matese lake. Lacustrine sediments also occur in the Volturno and Calore valleys (Bonardi et al., 1988). In the Picentini Mountains, which represent the SW border of the Irpinia area, Ferranti et al. (1996) suggested the existence of ENE-WSW trending low-angle normal faults that were active during the uppermost Pliocene. These features suggest that the E-W trending lineaments in the Irpinia area could be related to the same extensional event, while N-S trending lineaments, which do not always show significant morphological evidences, would represent transfer faults related to the E-W trending normal faults system.

3.2. The morpho-structures of the southern Tyrrhenian Sea

The morphotectonic analysis of the STS (Fig. 5) was mainly focused on its south-eastern margin, where the structural pattern is most likely associated with the extensional phases that affected the Marsili basin and the Campania Plain.

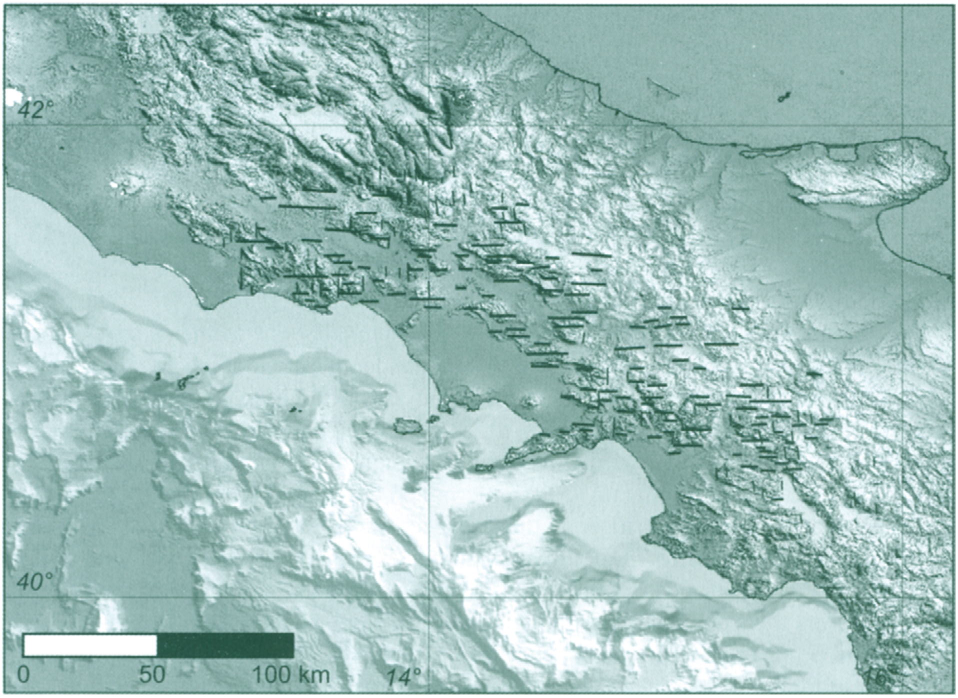

Figure 6. Tectonic lineaments of the Irpinia area detected from remote sensing data interpretation.

The Marsili basin, with its homonymous N15-N20 elongated seamount, is the younger of the two oceanic sub-basins that form the Tyrrhenian Sea (Marani, 2004 and references therein) (Fig. 1). Two NNE-SSW trending sets of faults, parallel to the 50 km elongated Marsili volcano, developed symmetrically in the basin floor. These features have been interpreted as horst and graben pairs at both edges of the Marsili volcano (Marani, 2004).

The SE margin of the STS is characterized by three en-echelon, N110 trending lineaments, represented by escarpments dipping towards the SW (Fig. 5). The southernmost of these lineaments connects the Palinuro seamount with the Poseidone ridge and corresponds to the northern margin of the Marsili basin. The intermediate and the northern lineaments correspond respectively to the SW-dipping escarpment of the Tacito seamount and to the Pontine Islands escarpment. Minor N-S and NNW-SSE trending lineaments connect these escarpments. Finally, the Sartori escarpment, composed of three N150 trending dextral en-echelon segments connected by NE-SW lineaments, is a further important lineament that characterizes the STS–TMAC transition (Marani, 2004).

4. Structural associations and determination of extension directions

The extension directions in the various sectors of the Apennine chain were determined by comparing the results of the morpho-structural analysis with data collected from the abundant geological literature.

In the NAA, the NW-SE trending regional normal faults and the associated NE-SW trending transfer faults indicate an NW–SE trending direction of extension (Fig. 4). Crustal extension in the internal (western) domain of the NAA took place, while the external (eastern) domain was subjected to thrusting and eastward migration of the thrust system (Patacca et al., 1990; Carmignani et al., 1995; Ferranti et al., 1996; Jolivet et al., 1998; Brunet et al., 2000; Rosenbaum et al., 2002). The internal sedimentary basins formed following the migration of the arc and become younger towards the east (Tavarnelli et al., 1998). Evidences of inactivity of thrusting and related folding in the external domain of the NAA in the last 800 ky (Di Bucci and Mazzoli, 2002) suggest that the ENE-directed migration of the NAA stopped in early Pleistocene times.

The structural complexity of the SAA (Fig. 5) is probably due to the superposition of two recent extensional phases. The difficulties in the identification of a coherent system of tectonic structures in this area led us to focus our attention to the more consistent morphotectonic features of the STS margin, which are directly linked to the relative motion between the SAA and the Western Tyrrhenian block and that were not subject to secondary deformation processes. Marani (2004) interpreted the Marsili seamount (0.78–0.1 Ma) as a N20-oriented spreading ridge. In this perspective we interpret the three en-echelon escarpments, represented by the Palinuro seamount–Poseidone ridge, the Tacito escarpment and the Pontine Islands escarpment, as part of a dextral N110 transform fault system, which transfers the extension throughout the eastern Tyrrhenian margin from the Marsili basin to the Campanian Plain area. Hence, in analogy with the NAA, if we associate the extension in the internal domain of the SAA with thrusting in the external domains, the resulting direction of arc migration is N110. Both the Sartori escarpment and the N140-N150 lineaments are incompatible with this kinematic framework, hence we suggest that they could be related with the formation of the older Vavilov basin (3.5 Ma) (Kastens et al., 1988).

The third extensional system is represented by E-W trending normal faults in the Irpinia area and related N-S transfer faults (Fig. 6). As stated above, this system is associated to a N-S direction of extension and is responsible for the moving apart of the two main arcs.

5. Chronology of the extensional phases

In order to determine the temporal sequence of the extensional tectonic events that affected the TMAC, we used the stratigraphic record from the Campania Plain, the Sele Plain, the Marsili basin and the Irpinia area. Further temporal constraints were derived from the volcanic events ages.

5.1. Extension in the Campania Plain – Bay of Naples basin

The Campania Plain is located in the merging area between the NAA and the SAA. It extends, from NW to SE, from the Aurunci Mountains and Roccamonfina volcano to the Sorrento Peninsula (Figs. 1 and 6). The Caserta Mountains, a NW-SE trending elongated relief, represent its NE limit, while its SW prosecution is open to the Tyrrhenian Sea. The basin is filled up with 3000 m Pleistocene sediments and volcanic rocks (Ippolito et al., 1973). Milia and Torrente (1999), based on chronostratigraphic data, indicated that NE–SW trending extensional faults in the Campania margin started to be active from 0.73 Ma. This extensional tectonics also affected the Bay of Naples, where seismic data show the presence of a NE-SW trending normal faults system of the same age (Milia et al., 1998; Milia and Torrente, 1999).

5.2. Extension in the Bay of Salerno – Sele Plain basin

The Sele Plain represents the on-shore prosecution of the Salerno Bay basin and is filled up with a thick succession of Quaternary sediments. A Pleistocene conglomeratic succession, known as the Eboli Conglomerates crop out on its northern margin and shows a well-developed system of conjugate N110 and N50 trending oblique faults (Cello et al., 1981). In the Salerno Bay, NW—SE trending extensional tectonics is testified by seismic data. In particular, the CROP-MARE M36 deep seismic reflection line (Scrocca et al., 2003) shows NE–SW trending normal faults and tilted blocks (Fig. 7). This confirms the connection between the on- and off-shore structures that we observed during the morpho-structural analysis. Furthermore, in the Salerno Bay, the Mina well (AGIP, 1977) showed a Plio-Pleistocene 2000–m-thick sedimentary deposit, and in particular 1000 m of Pleistocene sediments that suggest a strong tectonic subsidence affecting the basin during the Pleistocene.

5.3. Extension in the Marsili basin

The Marsili basin is a rectangular-shaped basin of roughly 80 × 50 km. It reaches a depth of more than 3000 m, and the Marsili seamount is located in its central part. The DSDP Leg 107 well 650 investigated the basin, drilling about 600 m of sediments laying above a basaltic basement (Fig. 8a). Kastens et al. (1988), on the basis of biostratigraphic and magnetostratigraphic constraints, suggest that inception of spreading in the Marsili basin took place between 1.87 and 1.67 Ma. Savelli and Schreider (1991) and Faggion et al. (1995) confirm this spreading inception age on the basis of the regional magnetic anomaly field (Fig. 8b).

5.4. Extension in the Irpinia area

The N-S extension that affected the Irpinia area is likely to be related with the formation of several Early Pleistocene lacustrine basins, for instance the Isernia and Boiano Basins (Bosi et al., 2004), and the Volturno and Calore valleys (Bonardi et al., 1988). As a matter of fact, these faults were reactivated in Middle Pleistocene times (Corrado et al., 2000; Calabrò et al., 2003), albeit with controversial kinematic interpretations.

5.5. Age of volcanic apparatuses

The oldest magmatic activity related with extensional tectonics in the Southern Apennines–Southern Tyrrhenian region is represented by the oceanic-spreading magmatism in the Marsili basin (1.8 Ma) (Kastens et al., 1988). This magmatism was followed by the

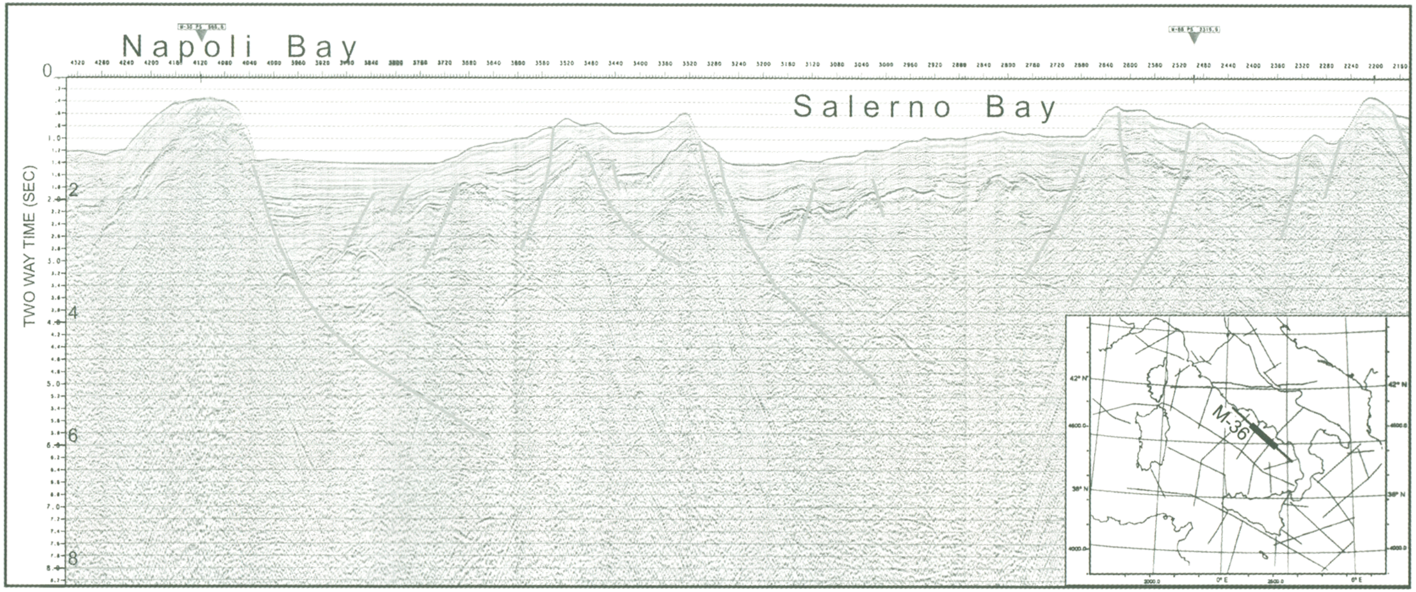

Figure 7. Seismic section and schematic line drawing from CROP-MARE M36 deep seismic line. The inserted box indicates the location of the line.

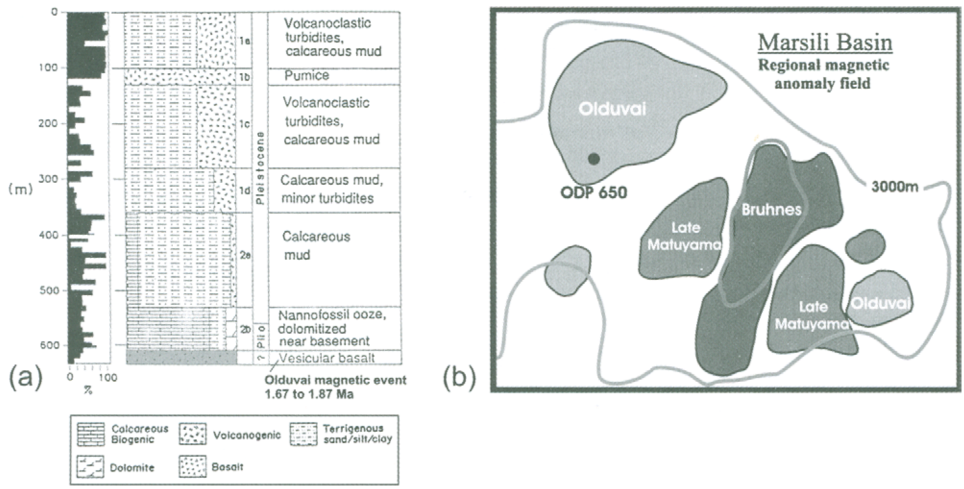

Figure 8. (a) Core log indicating the litostratigraphic units recovered at Site 650 (modified from Kastens et al., 1988); (b) Sketch map of the regional magnetic anomaly field in the Marsili basin. The closed line in correspondence of the Brhunes anomaly outlines the Marsili volcano (from Marani, 2004).

volcanic activity of the Palmarola Island at 1.6 Ma (Codeaux et al., 2004) and prosecuted northward in the Cimini Mts. (1.4 Ma) and Radicofani (1.3 Ma) (Serri et al., 2001). A second volcanic activity phase (0.8–0.1 Ma) led to the formation of Bolsena-Vico, Sabatini, Albani Hills, Ernici Mts., Ventotene Island, Marsili seamount, Roccamonfina and Vulture volcanoes (Serri et al., 2001). In the Campania Plain, the volcanic activity took place with the formation of the Ignimbrites (from 0.205 to 0.018 Ma) (De Vivo et al., 2001; Rolandi et al., 2003), which was followed by the Ischia, Campi Flegrei and Vesuvius activity (0.15–0.0 Ma) (Serri et al., 2001). In the STS, further volcanic apparatuses of the same age are: the Palinuro Smt, Alcione e Lamentini Smts and the Eolie Island (Serri et al., 2001).

6. Methods and constrains for the elaboration of the kinematic model

In order to describe quantitatively the geologic evolution of the Tyrrhenian Basin, we used a new software tool for the modelling of instantaneous motions of tectonic plates designed by one of us. Plate reconstructions were made using PCME, a computer program designed by Schettino (1998). The construction of a plate tectonic model for the geologic evolution of the Apenninic–Tyrrhenian Basin system required the following steps: (1) identification of the tectonic elements, that is, lithospheric blocks that were subject to independent motion during the considered time interval; (2) determination of the Euler poles describing relative movement between pairs of plates; (3) comparison between the predicted and observed structural patterns in order to confirm poles consistency; (4) compilation of a rotation model, which includes finite rotation parameters for pairs of plates. The tectonic elements were identified on the basis of first-order structures recognized by means of both the morpho-structural analysis and the spatial distribution of the volcanic apparatuses, whereas the rotation model was compiled based on both timing of activity of the first-order structures and regional first-approximation finite strain evaluation (e.g., either total shortening for the arcs or total extension for the basins).

6.1. Identification of the tectonic elements

The Apennine chain has been divided on the basis of homogenous structural patterns into two kinematic elements that, from Plio-Pleistocene times, moved independently with respect to the Eurasian reference plate. The two blocks are the Northern and the Southern Arcs (Fig. 9). A third element, the Western Tyrrhenian block, is considered as fixed with respect to Eurasia. The boundaries between these three kinematic elements are illustrated hereafter (Fig. 9). (1) The NW-SE trending volcanic lineaments of the Roman Comagmatic Province in the Latium region represents the boundary between the Northern Arc and the Western Tyrrhenian block. (2) The boundary between the Southern Arc and the Western Tyrrhenian is composed of three segments: the first segment runs from the Gaeta Basin to the Gortani Basin; the second segment corresponds to the N20 elongated Marsili Smt. The two segments are linked by a third lineament encompassing the Tacito and Palinuro-Poseidone escarpements. (3) The E-W

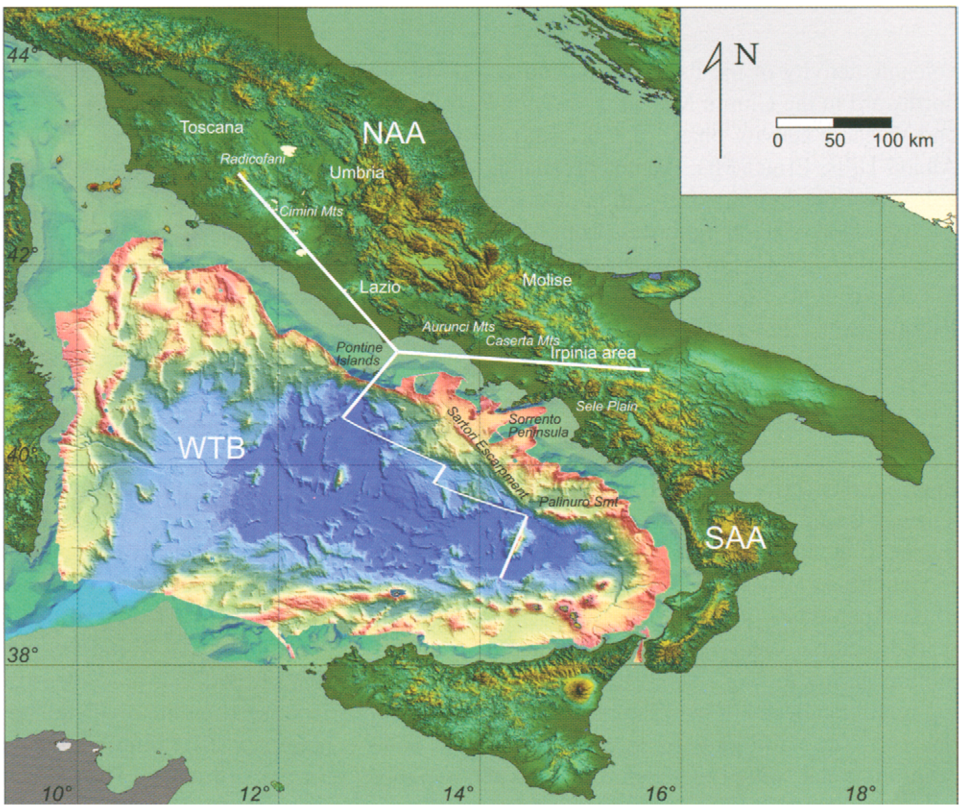

Figure 9. The three tectonic elements used to model the kinematic evolution of the Tyrrhenian margin of the Apennine chain. NAA, Northern Apennines Arc; SAA, Southern Apennines Arc; WTB, Western Tyrrhenian basin.

trending structural depression of the Irpinia area is the limit between the Northern and the Southern Arc. The individuation of this latter limit is also supported by gravimetric data (Fig. 2), which shows an E-W trending positive Bouguer magnetic anomaly in correspondence of the Irpinia area, indicating the existence of high-density body most likely related to a stretched lithosphere.

6.2. Determination of the Euler poles

The NE-SW trending system of strike-slip faults recognized by morpho-structural analysis of the central Apennines is consistent with a single rotation pole. This Euler pole, e_1, determines the instantaneous rotation of the Northern Arc with respect to Eurasia from the Uppermost Pliocene to the Lower Pleistocene and is located at (44.00°N, 11.20°E). Similarly, an analysis of the three N110-trending en-echelon escarpments of the Palinuro Smt-Poseidone ridge, Tacito Smt and Pontine Island escarpment led us to identify a unique stage of rotation of the Southern Arc about a pole e_2 located at (45.17°N, 17.51°E). However, this stage encompasses the whole time interval from the Uppermost Pliocene to the present.

Therefore, the Northern Arc, the Southern Arc and the Western Tyrrhenian block can be approximated as a three-plates system that can be described with the methods of instantaneous plate tectonics (McKenzie and Parker, 1974; Dewey, 1975). In this instance, the instantaneous pole of rotation of the Northern Arc with respect to the Southern Arc must be a continuously changing instantaneous Euler pole associated with structures that change their strike continuously.

6.3. Validation of the Euler poles

Our modelling software allowed us to generate grids of parallels and meridians for the Euler poles determined above. The reliability of the Euler poles was then assessed by comparing the pole grids with the actual structural lineaments recognized by the morpho-structural analysis. In fact, parallels and meridians of an Euler pole grid represent respectively strike-slip trends and normal faults. The results of such a comparison are illustrated in Figure10a and b. Good correspondence is evident between the main normal faults and the Euler poles meridians both in the Northern and Southern Arcs. In the Southern Arc, there is also a good match of the N110 and N20-N40 trending lineaments in the on-land areas with the e_2 parallels and meridians.

The validation method described above is also useful to discriminate the structural associations that are likely to be related with pre-Quaternary tectonic phases. For example, in the Southern Arc the N140-N150 trending lineament represented by the Sartori escarpment mismatched the e_2 grid. We interpret this first-order structure as the result of a previous tectonic phase, most likely related to the opening of the Vavilov basin (3.5 Ma). This hypothesis is supported by the fact that the Sartori escarpment shows variable morpho-structural features along its length (Fig. 5). In its NW segment the lineament is represented by a sharp ridge, probably related with strike-slip tectonics, while the SE segment is represented by an escarpment separating two portions of sea floor at different depths, thus indicative of normal faulting. These features suggests that the SE segment of the Sartori

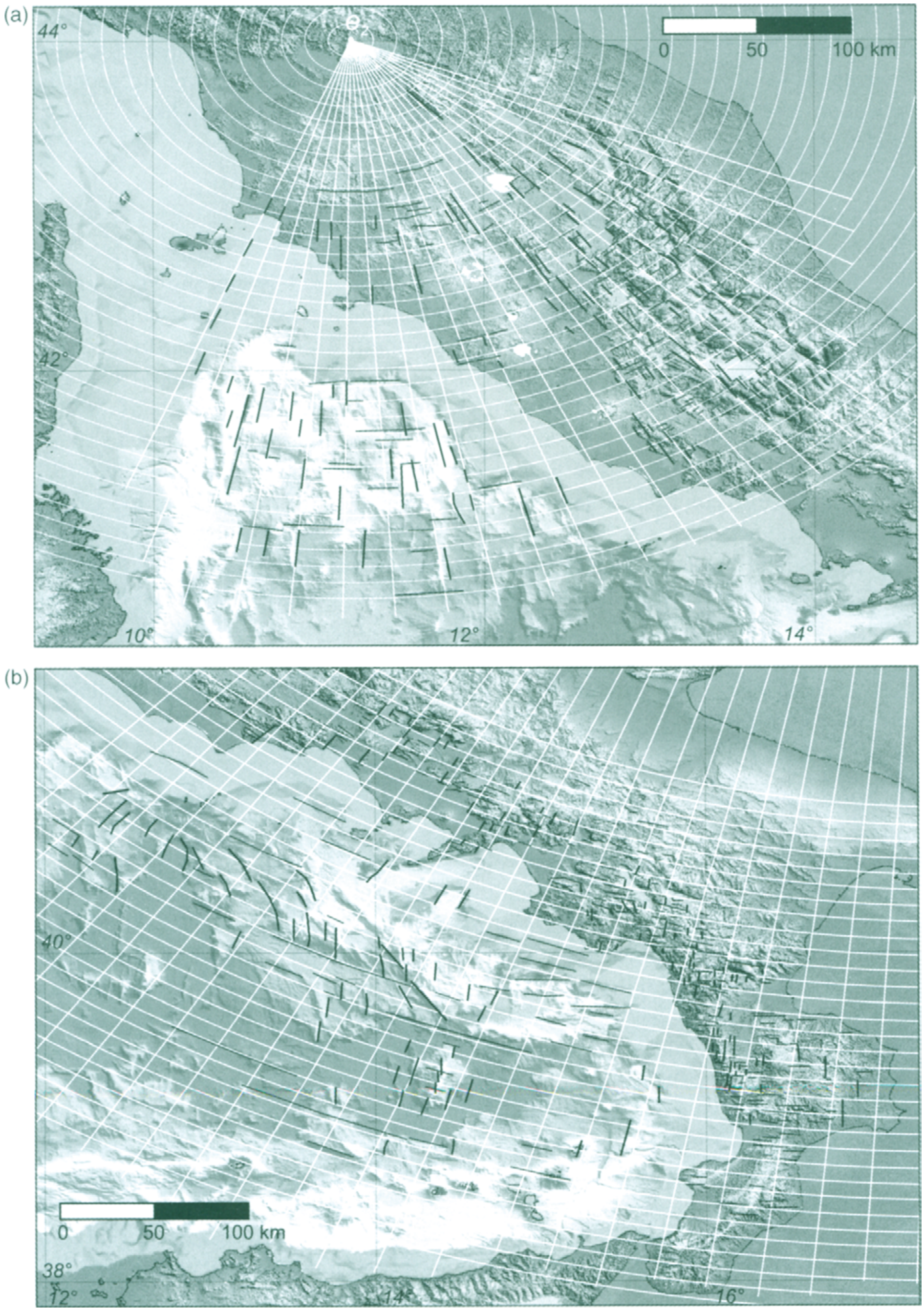

Figure 10. Comparison between the structural lineaments recognized by the morpho-structural analysis and the Euler pole grids for the rotations of the (a) Northern Apennine Arc and (b) the Southern Apennine Arc. Note the good correspondence between the main normal faults and the Euler poles meridians both in the Northern and in the Southern Arcs. In the Southern Arc, there is also a good match of the N110 and N20-40 trending lineaments in the on-land areas with the e_2 parallels and meridians.

line, which was originally related to strike-slip faulting, was reactivated as a normal fault during the activity of the superimposed N110 right-lateral strike-slip faults system widespread in the SAA. Further evidences of pre-Quaternary N140-N150 trending strike-slip tectonics, most likely related with the same tectonic phase of the Sartori line, have been recognized in Calabria (Van Dijk, 2000).

6.4. *Finite strains, strain rates and finite angular rotations of the Southern and Northern Arcs*

Euler poles alone do not allow a complete representation of the tectonic evolution of a region. They only constrain local directions of extension, strike-slip or convergence between two plates. In order to quantitatively describe the total deformation, a determination of the angles of rotation about these poles is needed. A technique for determining the angle of rotation of the Southern Arc with respect to the Western Tyrrhenian block is to move back the arc by the angle that removes the whole oceanic crust formed during the spreading episode of the Marsili basin.

We estimate the width of Marsili oceanic crust to be ~80 km on the basis of the magnetic anomaly field and the Moho depth. Hence, the total angle of rotation about the SAA pole e_2 for the closure of the Marsili basin results to be 6.93°. This stage started during the Olduvai polarity chron (~1.87 Ma) and lasted till about 0.78 Ma (Matuyama–Bruhnes transition), when spreading ceased in the Marsili basin and extension jumped south-eastward in the Aeolian Island Arc. The corresponding spreading rate and direction result to be 77.65 mm/yr, N110E at 39.3°N, 14.4°E.

During the second stage, from ~0.78 Ma (Matuyama–Bruhnes transition) to the present time, the migration of the SAA occurred about the same Euler pole e_2. If we assume that the extension rate remained the same as the previous stage, we obtain an angle of rotation of 5.00° about the SAA pole e_2 from 0.78 Ma up to the present. In the Marsili basin, still continuing up-welling of magma at the (now extinct) spreading centre contributed to the edification of the Marsili Seamount. In fact, the youngest volcanic rocks in this region are ~0.1 Ma in age (Selli et al., 1979).

The angle of rotation of the Northern Arc was calculated indirectly on the basis of the kinematic parameters of the three-plates system and the observed structural pattern in the Irpinia area. As already mentioned, this pattern cannot be described by a single pole of instantaneous rotation, because it is the characteristic of a continuously migrating Euler pole. However, an average N-S direction of extension can be identified (Fig. 11). Several different patterns can be predicted by varying the rate of the angular velocities of the two arcs. Let Ω_N and Ω_S be the angular velocities of the Northern and the Southern Arcs, respectively. Using specific software, we noted that in order to obtain a mean N–S direction of extension it was necessary that the following identity was satisfied:

$$\Omega_N \cong 1.5\Omega_S \tag{1}$$

The parameter Ω_S is determined by the total angle of rotation (6.93°). Hence, the application of Equation 1 allowed us to estimate the total angle of rotation of the Northern Arc as 10.40°. Figure 11 illustrates the predicted pattern of relative linear velocities between the Northern and the Southern Arcs.

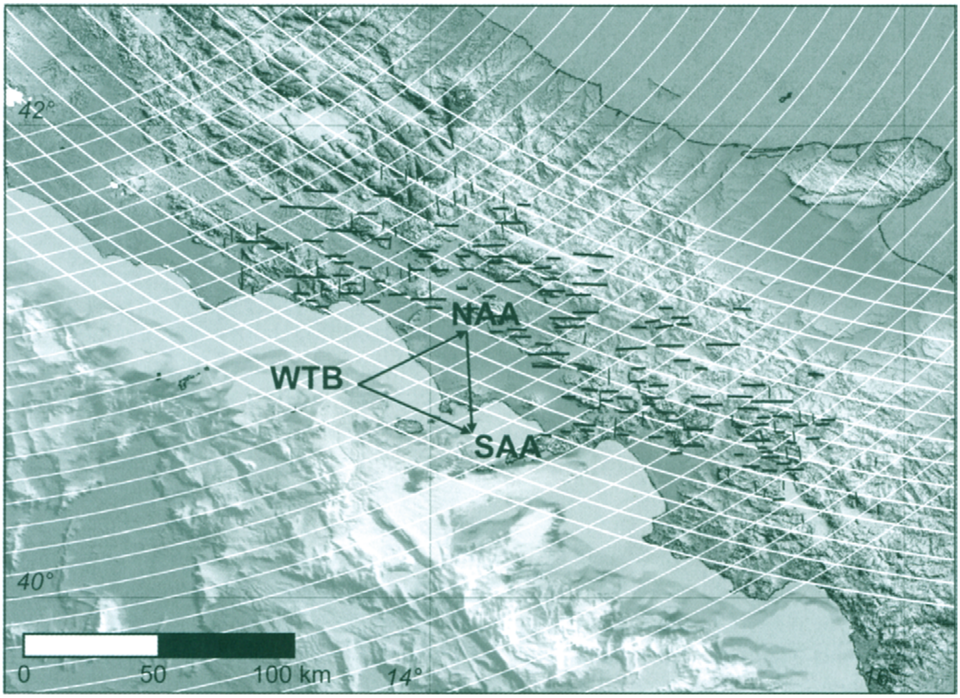

Figure 11. Predicted pattern of the relative linear velocities between the Northern and the Southern Arcs. It was calculated on the basis of the kinematic parameters of the three-plates system and the observed structural pattern in the Irpinia area. For further explanations see the text.

The simultaneous rotation of the Northern and Southern Arcs ceased at about 0.78 Ma, when the Northern Apennines chain stopped its migration. Starting from this time, only the Southern Arc continued its ESE motion. As already mentioned, the angle of rotation for this additional stage (~5°) was estimated on the basis of the assumption that the angular velocity of the Southern Arc remained approximately constant.

7. Discussion

In this section, we discuss the geologic consequences of our kinematic model as well as unsolved problems. Although the kinematic model described above was built on the basis of estimated expansion rates in the Marsili basin since 1.87 Ma, the process initiated some time before, perhaps at the same time of the cessation of spreading in the Vavilov basin (3.5 Ma, Kastens et al., 1988). In this hypothesis, the STS would be subject to a continuous process of rifting-spreading since the Early Pliocene through a series of ridge jumps.

During the first stage, between 3.5 and 0.78 Ma (Fig. 12a), the anticlockwise rotation of the Northern Arc generated both the NW-SE trending normal faults and the NE-SW trending strike-slip faults in the central-northern Apennines. The SE-directed migration of the Southern Arc was associated to extension and spreading in the Marsili basin as well as transcurrent tectonics along N110 strike-slip faults in the SAA and in correspondence of the Tyrrhenian escarpments. The NE-SW and N-S trending normal faults in the Tyrrhenian margin are interpreted as releasing step-over associated to the N110 trending strike-slip faults. The relative motion between the two arcs produced the E-W trending normal faults in the Irpinia and Campania Plain area, together with the associated N-S trending strike-slip faults. Finally, incipient volcanism took place in the Palmarola volcanic apparatus (1.6 Ma) and in the Cimini Mts (1.4 Ma), while magmatic intrusions occurred in the Radicofani area.

In the second stage (0.8 Ma–present time) (Fig. 12b), the N-E directed migration of the Northern Arc either considerably slowed down or even ceased at all, while the Southern Arc continued migrating towards the ESE. The northern limit of the Southern Arc, represented in the previous stage by the Irpinia area, is now characterized in the Campania Plain by a new generation of NE-SW trending normal faults and NW–SE trending strike-slip faults, while in the Irpinia area both the previous E-W trending

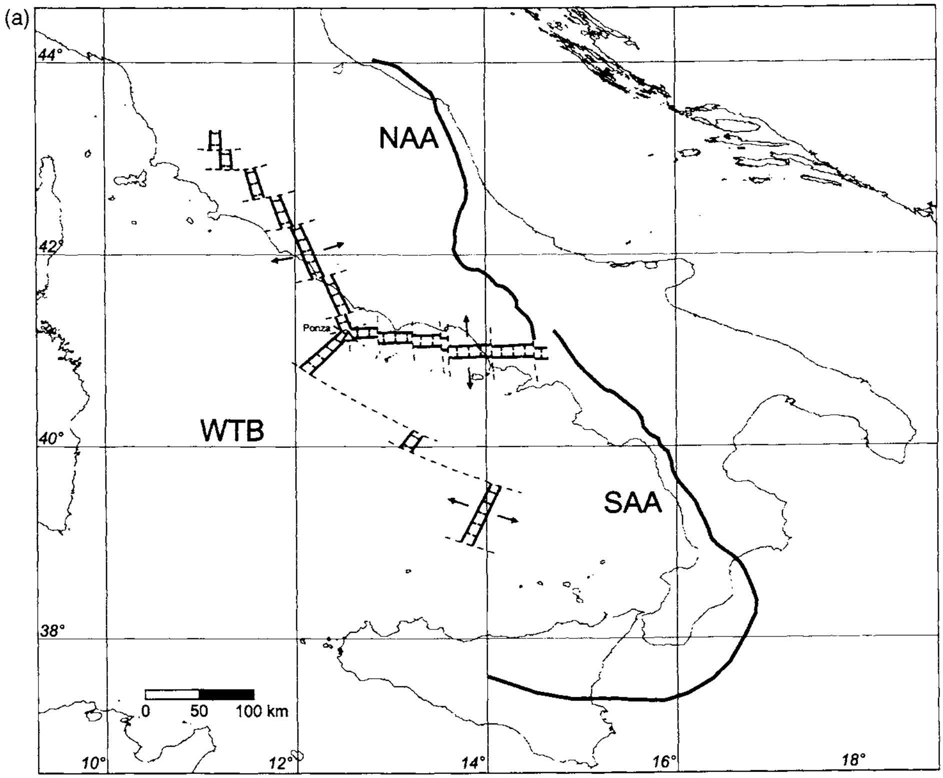

Figure 12. Kinematic model of the Tyrrhenian–Apennines system showing the correlation between the extension and volcanism in the back of the two main arcs. (a) Initial configuration of the three tectonic elements (Middle Pleistocene times); (b) first stage, between 3.5 and 0.78 Ma; (c) second stage, from 0.78 Ma to present time. See text for further discussion.

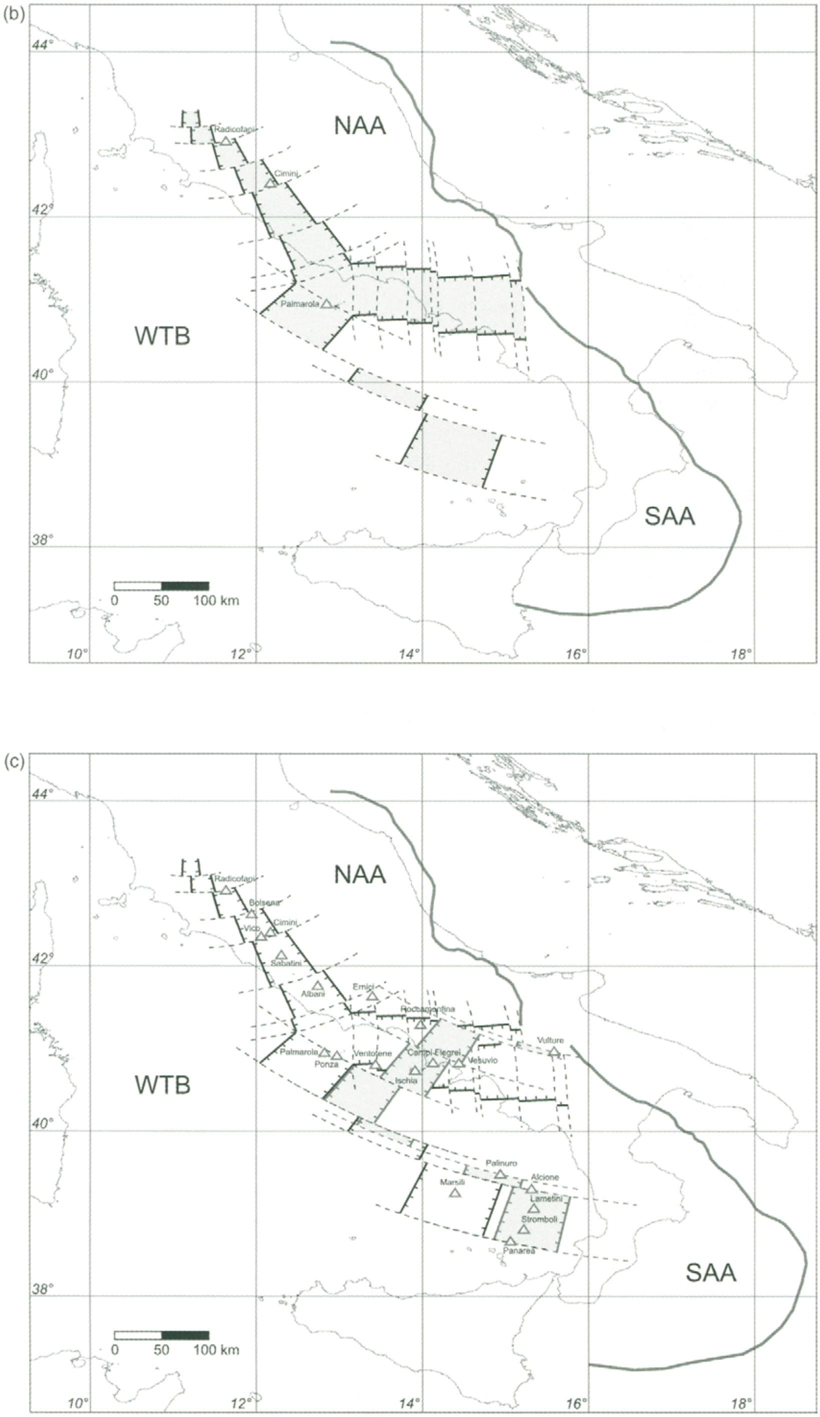

Figure 12. *(Continued)*

normal faults and N-S strike-slip faults are reactivated respectively as left- and right-lateral transtensional faults transferring the motion of the Southern Arc into the Bradanic foredeep. We put forward the idea that emplacement of the Vulture Mountain volcano is related to this latter transfer fault system. The extensional tectonics in the Campania Plain is transferred into the Southern Tyrrhenian through the previous formed N110-trending strike slip-faults.

Spreading in the Marsili basin stopped and the spreading centre jumped to its present position along the Aeolian Islands (0.5 Ma), Alcione (0.35 Ma) and Lametini (0.35 Ma) volcanic lineament. In a short time span between the end of the first stage and the beginning of the second one, a massive volcanic activity took place contemporaneously in correspondence of the three extensional axes (Fig. 12b). The most recent volcanic activity in the TMAC – Ignimbrites of Campania Plain (from 0.205 to 0.018 Ma), Ischia (0.15 Ma), Campi Flegrei (0.03 Ma) and Vesuvius volcano (0.03 Ma) – is limited to areas affected by extensional tectonics related to the second stage of the tectonic evolution.

In this reconstruction of the tectonic evolution of the Campania Plain, the location in present-day coordinates of the extinct triple junction between the Northern Arc, the Southern Arc and the Western Tyrrhenian block is not easy to determine. In fact, the prevalence of diffuse deformation (rifting) makes it difficult to determine a unique point of conjunction of three distinct "plate boundaries". Furthermore, in areas of incipient rifting the migration of the lithosphere extensional axes can follow different trajectories depending on the symmetry of the rift system. In other words, extension axes migration follows the same rules of oceanic ridges when extension is symmetric (i.e. when they follow the McKenzie rifting model, 1978), while they go behind the motion of the upper plate when extension is asymmetric (i.e. in the Wernicke rifting model, 1985) (Fig. 13a,b). In the TMAC, there is not enough data to constrain the symmetry of the rifting phases. Therefore, it is not possible to determine accurately the position of the extensional axes and the associated migration of the triple junction. Nevertheless, a qualitative composition of the vectors for the relative motion of the Northern Arc with respect to the Southern Arc suggests that the triple junction migrated towards east.

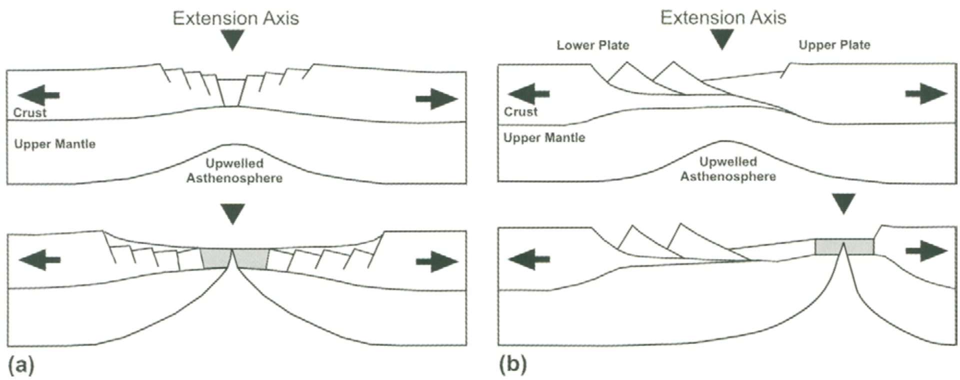

Figure 13. Two end-member model for continental extension. (a) In the symmetrical extension model (i.e. McKenzie pure-shear model, 1978) the extension axe remains fixed in the middle of the two conjugate margins. (b) In the asymmetrical extension model (i.e. Wernicke simple-shear model, 1985), after the inception of oceanic spreading the extension axe remains fix with the upper-plate margin.

8. Conclusions

The relative motion of the northern and southern Apennines chains was reconstructed on the basis of the geologic and kinematic constraints described above. When those constraints are either lacking or insufficient, tectonic motions were established by both trial-and-error tests or indirect methods based on vector calculation. The first preliminary result of this technique was the identification of two distinct rotation stages for the Apennine chain. During the first stage, from 3.5 to 0.78 Ma, the Northern and the Southern Arcs migrated independently with respect to the chosen reference system represented by the Tyrrhenian Sea–Sardinia–Corsica–Eurasia blocks. In the second stage, from 0.78 Ma to present, the Northern Arc stopped migrating, as suggested by cessation of thrusting and related folding in the external domains of the northern Apennines (Di Bucci and Mazzoli, 2002). Conversely, the Southern Arc continued migrating towards the SE. Therefore, the N-S extension in the Campania Plain is the result of the relative motion of the NAA with respect to the SAA during the first stage only, whereas the present-day NW-SE extension in this area, which is characterized by intense volcanism (e.g., Ignimbrites, Ischia, Campi Flegrei, Somma–Vesuvius), is related to the migration of the SAA with respect to a NAA block that is now fixed to the Western Tyrrhenian block. This migration is kinematically linked, through a system of right-lateral en-echelon transfer faults, with the extension centre of the STS located near the Alcione–Lametini–Aeolian Island Arc volcanic lineament.

This model of migration of the Apennine chain is based upon the assumption that the whole mountain range can be considered as a system of only two rigid arcs. This approximation is valid if we consider as negligible the internal deformation of the Southern Arc along the N110 sinistral strike-slip fault, which separates the southern block in at least two distinct tectonic elements (Dewey et al., 1989; Knott and Turco, 1991). Such separation determined a diachronism in the foredeep activity. In fact, tectonic activity in the Bradano trough ceased 0.65 Ma (Patacca and Scandone, 2001), whereas the Ionian foredeep can be still considered as active on the basis of the deep seismic activity related with the Tyrrhenian slab subduction. Conversely the Northern Arc is clearly rigid or quasi-rigid during the considered time interval, except for its southernmost end (Molise). In conclusion, the simplifying assumption of rigidity of the two arcs does not affect the model presented in this paper, which only aims at describing the process of extension and associated magmatic activity in the Tyrrhenian margin of the Apennines chain. Finally, although the model presented above does not take into account many aspects of the complex tectonic evolution of the TMCA, it realistically assembles in a unique kinematic framework the first-order structures that are observed in the Apennine area and in the Tyrrhenian basin, in order to explain the relationships existing between the main structural features of this region.

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