TYRRHENIAN BASIN AND APENNINES. KINEMATIC EVOLUTION AND RELATED DYNAMIC CONSTRAINTS

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ABSTRACT. The post-Oligocene kinematic evolution of the central Mediterranean region is synthetically described. The proposed reconstruction is based on a comparative study of tectonically- controlled sedimentary sequences and of coeval tectonic features in areas experiencing stretching (Algero-Provençal Basin, Tyrrhenian Basin) and shortening (Apennines). The derived step by step palinspastic reconstruction at Langhian times states a number of constraints for the geodynamic processes that affected the area during Neogene and Quaternary times. Both continental (often thinned) and oceanic lithosphere were involved in subduction processes. The former prevailed in the northern sector, while both oceanic and continental lithosphere were present in the southern area. The long duration of the subduction processes in the southern sectors may be related to the existence of large portions of sinking oceanic lithosphere which dragged down intervening portions of continental lithosphere.

1. Introduction

Four major geodynamic elements occur in the central Mediterranean region. The Algero-Provençal Basin is a back-arc area that developed between the upper Oligocene and the lower-middle Miocene. The Corsica-Sardinia "Block", is a fragment of normal continental crust which acted as a frontal volcanic arc, translated and rotated, during the opening of the Algero-Provençal Basin. The Tyrrhenian Basin is another back-arc area that started stretching since upper Miocene times. The Apennines are an orogenic system that records shortening and deformations coeval to the development of the previous domains.

Following the "roll-back" model proposed by Malinverno and Ryan (1986), the opening of the extensional basins may be interpreted as a consequence of a fast flexure-retreat of the subducting foreland lithosphere, which exceeded the convergence rate between Africa and Europe. The evolution of the central Mediterranean region followed two main steps.

1. From about 30 to 13 Ma ago the opening of the Algero-Provençal Basin and the drifting/rotation of the Corsica-Sardinia "Block" took place. This interval (during which Sardinia acted as a volcanic arc), is longer than that one proposed in the past (see Montigny et al. 1981); nevertheless, new paleomagnetic data (Vigliotti and Langenheim, 1992) suggest that rotation of Sardinia was quite complex and at least in some areas it was not completed in Langhian times. The Algero-Provençal basin developed inside an area previously consisting of normal continental lithosphere and representing the European foreland of the Cretaceous-Paleogene Alpine chain. The newly individuated Corsica-Sardinia "Block" acted, during its Neogene evolution up to late Tortonian times, as the hinterland of an eastward-migrating arc-

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trench system. The evolution of this arc-trench system is recorded in the Apennine units piled up during the drifting/rotation of the "Block". Some of these units were also affected, during shortening, by greenschist metamorphism.

2. From about 8 Ma ago to present, the Tyrrhenian area underwent back-arc-type extension. Large portions of the previous mountain chain were involved in the extensional processes; new compressional deformations (post-Tortonian Apennines) were in turn produced, following the further outward migration of the arc-trench system.

The Apenninic chain as a whole is a complex pile of thrust and nappe units, transported towards the Padan-Adriatic-Ionian- Hyblean foreland starting from Late Oligocene times. As a result of the post-Tortonian evolution, the Apenninic chain (including Calabria and Sicily) is presently split into two major arcuate features: the northern and the southern Apenninic arcs (Fig. 1). They merge in Central Italy along a marked feature, called Ortona-Roccamonfina Line, which acted as dextral strike-slip transfer during Quaternary times (Patacca et al. 1991). In parallel, also the Tyrrhenian Basin can be subdivided into two sectors, respectively N and S of a prominent lineament running W-E from northern Sardinia to Campania (41° N Line in Fig. 1). North and south of this late Neogene transfer, extension rates were markedly different. Only to the south, extension was so high to generate oceanic lithosphere in two small districts.

Patacca et al. (1990) proposed a palinspastic restoration of the Apenninic paleogeographic domains in late Tortonian times and reconstructed a possible kinematic evolution of the Tyrrhenian-Apennine couple. The major tectonic events were defined by the recognition of the regional structural features (listric faults in the extensional areas, thrust fronts and lateral ramps in the compressional ones) and by a careful stratigraphic analysis of the sedimentary sequences deposited under tectonic control. The investigation was focused on three different structural settings:

- extensional areas, where syn-rift clastic wedges are widespread in half-graben basins produced by listric faults;
- mountain belt, where piggy-back basins have developed on top of the advancing thrust sheets;
- flexure zones, where siliciclastic flysch deposits were filling active foredeep basins produced by the progressive flexure retreat of the subducting foreland lithosphere.

We refer to Patacca et al. (1990) for most of the references which are not reported here for the sake of readability. In this paper, we tentatively extend the palinspastic restoration of the central Mediterranean domains to Langhian times, in order to compare the early-middle Miocene tectonic evolution of the area (when the Algero-Provençal Basin, Corsica and Sardinia were still active elements) with the late Miocene-Quaternary one. We shall also discuss some major implications concerning the subduction processes and the nature of the consumed foreland lithosphere.

Figure 1. Structural sketch of the Apennines and Tyrrhenian Basin. The base-of-Pliocene/Quaternary isobaths (1, in kilometres) show the deformation pattern of the foreland areas. In the northern Apenninic arc, the foreland appears still sinking beneath the thrust belt. The Ortona-Roccamonfina Line (OR Line) acts as lateral ramp of the northern arc. The front of the thrust belt (2), major post-Tortonian thrusts (3), normal faults (4), strike-slip faults (5), antiforms (6) and synforms (7) show the regional structural trends. Areas with widespread magmatic activity (8 volcanites, 9 intrusive bodies) are also indicated.

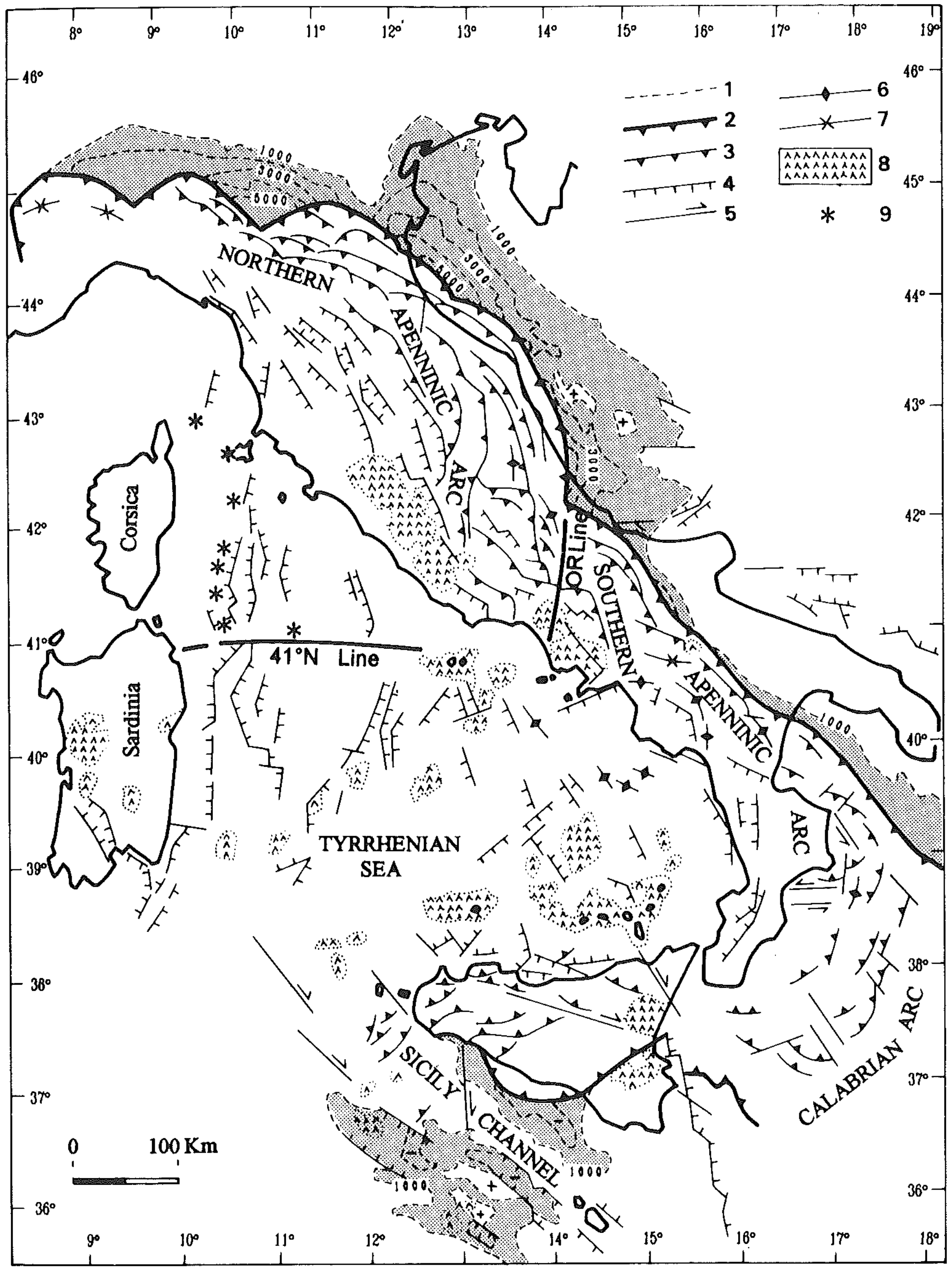

Figure 1

2. Palinspastic restoration and kinematic evolution.

Fig. 2 is a palinspastic sketch of the study region reconstructed at Langhian times (about 16 Ma), when several south-Apenninic domains where supplied by Africa-deriving Numidian sands (see Patacca et al. 1992). At that time, the mountain chain included the Ligurian and Calabrian nappes carrying a series of piggy-back basins (e.g. Stilo-Capo d'Orlando, Albidona, Ranzano- Bismantova sedimentary sequences, Bonardi et al. 1980, 1985; Ricci Lucchi 1986). In the south, the compression front had not reached yet the Sicilide domain, where in fact Langhian Numidian sandstones were conformably deposited over Aquitanian-Burdigalian sediments rich in volcaniclastic material. The Numidian input also reached the San Donato domain, when the latter began to be incorporated in the foredeep basin (Patacca et al. 1992). Greenschist metamorphism affecting both the Verbicaro and the San Donato units points (Amodio Morelli et al. 1976) to a collision between the Sardinia "Block" and the Apulian continental margin post-dating the Langhian (age of the Numidian sandstones). In the Northern Apennines, on the contrary, the Langhian mountain chain already included the equivalent of the Sicilide units (Canetolo unit) and the equivalent of the Verbicaro and San Donato units (Tuscan nappe and Tuscan metamorphic units). Greenschist metamorphism in the Apuane-Montagnola Senese units (Carmignani et al. 1978; Kligfield et al. 1986) and crustal doubling in Tuscany (Roeder 1990) suggest a pre-Langhian collision between the Corsica "Block" and the Padan-Adriatic continental margin, with development of a deep-seated shear zone within the Padan-Adriatic crust. These facts strongly support the idea that Sardinia had not yet completed counterclockwise rotation during the Langhian (Vigliotti and Langenheim, 1992), whilst Corsica had already reached, in that time, the present- day position.

In Fig. 2, the Verbicaro and the San Donato domains have been linked to the western Apenninic platform, the Verbicaro domain representing the original inner slope of the shallow platform. The connection between the western Apenninic platform and the Panormide domain are still questionable and the more internal position of the Panormide carbonate domain suggested in Fig. 2 is merely hypothetical.

Another open problem is represented by the original position of the Lagonegro basin, which is usually considered the southern continuation of the Molise basin, located between the western platform and the Inner Apulia one (e.g. Mostardini and Merlini, 1986; Casero et al. 1988). Nevertheless, some tectonic features, together with stratigraphic considerations, suggest a more internal relocation of the Lagonegro basin. An important tectonic feature is the occurrence of Ligurian and Sicilide slices tectonically sandwiched between the upper and the lower Lagonegro units, which prove the out-of-sequence nature of the tectonic doubling.

Figure 2. Palinspastic sketch of the central Mediterranean region in Langhian times. According to the picture, Sardinia did not complete rotation and a calc-alkaline volcanic arc was still active in the western part of the island. Within the Apenninic domains, basinal areas possibly floored by oceanic crust (Sicilide realm, South Molise-Ionian basin) and areas occupied by persistent shallow platforms (Panormide realm, western platform, Inner Apulia platform and Apulia platform s.str.) are roughly delimited. The front of the thrust belt in the Alps and Apennines, as well as the Insubric Line are merely geographic references. The hatched area between the Po-Adriatic foreland and the Southern Alps-Dinarides represents the amount of shortening related to the Europa-Africa convergence from Langhian times. This shortening is quite small, compared to the Apennine shortening related to the roll-back of the Padan-Adriatic-Ionian lithosphere.

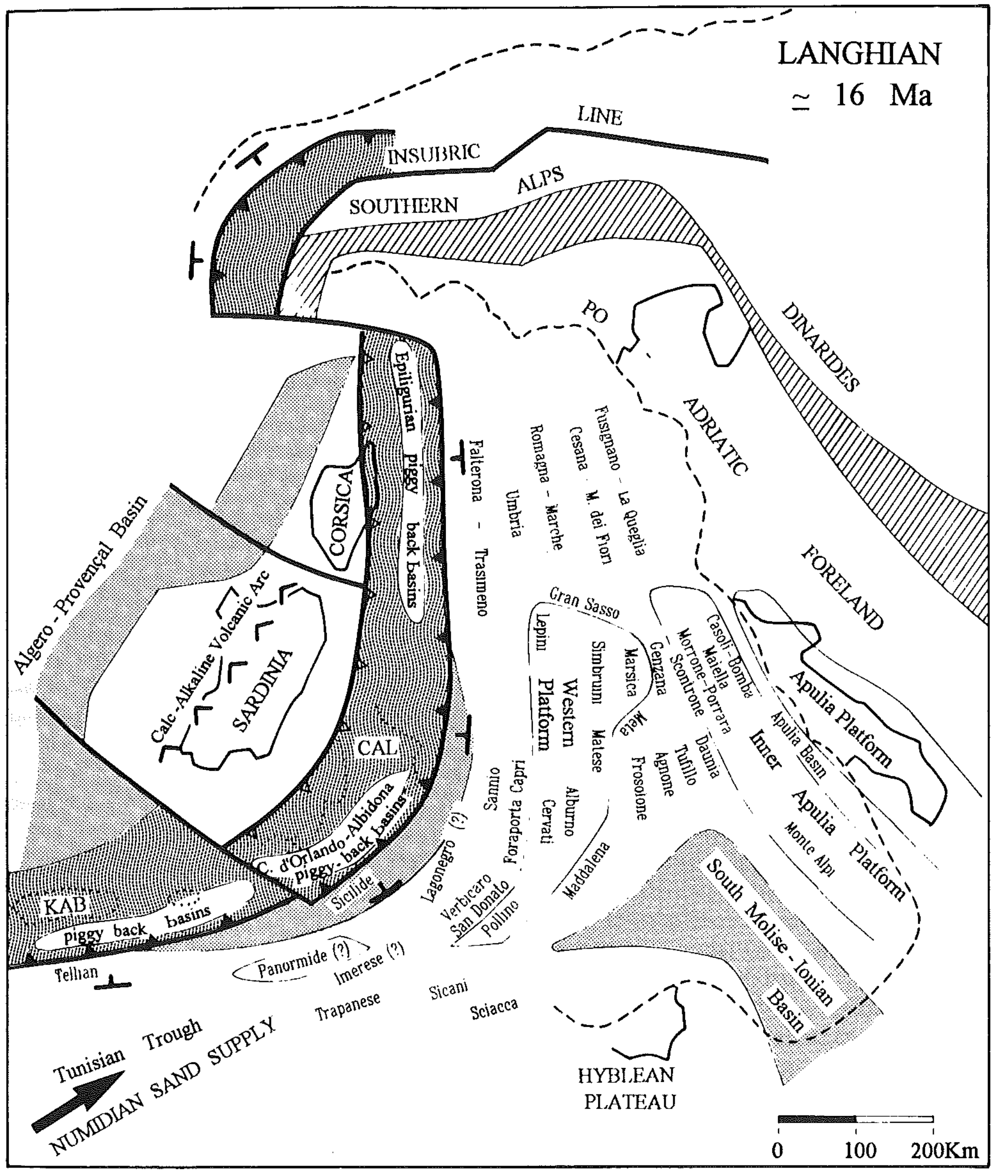

Figure 2

In addition, field evidences clearly show that the tectonic superposition of the western-platform carbonates (together with the Sannio and the Sicilide nappes) over the Lagonegro units is systematically an out-of-sequence thrust contact, not older than Messinian, with the footwall units previously doubled. Two stratigraphic considerations further stress the proposed paleogeographic attribution. The most important one is that no post-Langhian deposits occur in the Lagonegro sequences. In the Molise units, on the contrary, post-Langhian sequences are preserved everywhere, with their upper part represented by thick flysch deposits of Messinian age. The second indication is that no rocks older than middle-upper Liassic are known in the Molise units, whilst the Lagonegro basin became a deep-water furrow already in Middle Triassic times. This matches the observation that no extensional tectonics older than middle-upper Liassic has been found so far either along the eastern margin of the western platform or along the western margin of the Inner Apulia platform.

The last questionable relocation concerns the Sannio domain. The Sannio unit has been often confused, following Ortolani et al. (1975), with the Lagonegro units in spite of their different geometric position (the Sannio unit tectonically overlies whilst the Lagonegro units tectonically underlie the carbonate thrust sheets) and in spite of some different characteristics of the respective sedimentary sequences (see Patacca et al., 1992). The tectonic position of the Sannio unit and the occurrence of Serravallian siliciclastic flysch deposits in the sedimentary sequence univocally fix its original position west of the western Apenninic platform, since the latter was incorporated in the foredeep basin during upper Tortonian times.

A relocation of the San Donato and Verbicaro domains along the inner margin of the western Apenninic platform brings as a consequence that the collision between the Sardinia "Block" and the Apulia continental margin took place after the deposition of the youngest deposits of the Sannio unit, that is not before the early Serravallian. This age is not in conflict with the recent paleomagnetic results on Sardinia of Vigliotti and Langenheim (1992) and concides with the end of the calc-alkaline volcanic activity in that island at about 13 Ma (Savelli et al. 1979).

Referring to Fig. 2, we are going now to describe the main steps of the regional kinematic evolution.

Upper Oligocene - Langhian

Starting from kinematic conditions of a neutral arc, where convergence rate and rate of flexure retreat of the subducting lithosphere were approximately equal, an increase in the rate of foreland flexure-retreat caused back-arc opening in the Algero-Provençal Basin, drifting of Corsica-Sardinia, and forward migration of the thrust belt-foredeep system. Due to the spatial distribution of the paleogeographic domains, Corsica collided with the Tuscan realms and the foredeep shifted east of the shear zone, reaching the Falterona-Trasimeno domain. From this times onwards, no oceanic crust was available in the northern part of the study region.

Wide portions of oceanic or strongly-thinned continental crust (Sicilide, Sannio and possibly Lagonegro domains) were still available in the south, so that spreading in the Algero-Provençal Basin, drifting of Sardinia and progressive outward migration of the thrust belt-foredeep system continued, the accretionary wedge being constituted of rather thin units derived from the sedimentary cover detached from the subducting lithosphere.

Serravallian - Lower Tortonian

Around 13 Ma Sardinia collided with the Verbicaro and San Donato domains, causing deep-seated shear zones and greenschist metamorphism. No evidences of lower Tortonian foredeep basins have

been found up to now in the Southern Apennines.

In the northern sectors, convergence rate and rate of flexure retreat had to be rougly equal, as it is suggested by the progressive eastward migration of the thrust belt-foredeep system (from the Falterona-Trasimeno to the Umbria-western Romagna domains) without clear evidences of back-arc extension between Corsica and the Apennines. Piggy-back basins developed (see, e.g. Ponsano and Bismantova sedimentary sequences, Mazzei et al. 1980; Ricci Lucchi 1986) on top of the advancing thrust sheets.

Upper Tortonian - Lower Messinian

At the present state of the art, we are not able to evaluate how long time elapsed between the incorporation into the foredeep of the platform domains not yet reached by the Serravallian compression and the enucleation of the earliest extensional features in the Southern Tyrrhenian area. In any case, during late Tortonian times the rate of flexure retreat of the foreland lithosphere had to exceed the convergence rate both in the Northern an Southern Apennines, since back-arc extension began at that time in the whole Tyrrhenian region. Here, the 41° N lineament acted as an important transfer fault which allowed for larger amounts of back-arc extension, flexure retreat, and forward migration of the compression fronts in the southern areas. In the Southern Tyrrhenian basin, limited portions of oceanic lithosphere may have been emplaced near the end of this interval.

Upper Messinian - Lower Pliocene

Severe rifting occurred in the southern Tyrrhenian area across the Central Fault, followed by oceanic crust emplacement in the central bathyal plain. North of the still active N 41° N lineament, moderate extension occurred in the northern Tyrrhenian Sea and Southern Tuscany accompanied, in the mountain chain, by eastward migration of the compressional fronts. In the central Apennines, arcuate features, corresponding to out-of-sequence thrusts, widely developed from the Sibillini mountains to the Gran Sasso-Genzana area. These features, which sometimes form high angles with the strike of the previous compressional structures, produced block rotations in the concave portions of the arcs (Mattei et al., 1991). In the Southern Apennines and Calabria, data on the buried foredeep deposits are very poor, due to the geometry of the thrust belt (duplex system) and to the insufficient subsurface information. Some indications regarding the compression front migration are supplied by the piggy-back- basin deposits unconformably overlying the roof units of the duplex.

Upper Pliocene

The upper Pliocene kinematic evolution of the study region does not markedly differ from the lower Pliocene one, with the main variant represented by a southward migration of the arcuate features in the thrust belt (see Patacca et al. 1991). Near the end of the Pliocene, the Apennine compression front reached the present-day position in the Ortona-Lucera segment, suggesting the end of the Adriatic-Apulia flexure retreat in the area.

Quaternary

During the Pleistocene, the differentiation of the two Apenninic arcs became more and more pronounced. In the northern Apenninic arc, extension and compression still followed SW-NE vectors, with dextral transpression along the Ortona-Roccamonfina Line (eastern wing of the arc). In the southern arc, on the contrary, flexure retreat and thrust belt-foredeep migration progressively ceased from north to south (near the Pliocene-Quaternary boundary in the Molise-Daunia segment; about 1 Ma ago in the Campania- Lucania segment, see Cinque et al. 1992).

Flexure retreat of the Ionian lithosphere and migration of the Calabrian Arc were still active when the previous south-Apenninic segments were already undergoing "isostatic" rebound. We are not able, however, to establish whether roll-back processes are still working in the Calabrian Arc or they have ceased in late Pleistocene-Holocene times. It is interesting to point out that the rhombic Marsili basin, floored by young oceanic crust, opened just back of the Calabrian Arc. This belt was still moving toward the Ionian Sea when the Campania-Lucania Apenninic front was already near to the present-day position.

3. DISCUSSION AND CONCLUSIONS

As already described, the post-Tortonian evolution of the area had different kinematics in the northern and southern sectors. The northern Tyrrhenian Basin experienced modest rifting and crustal thinning, whilst the southern basin was severely stretched, with emplacement of oceanic crust. In parallel, the Apenninic chain evolved into two arcs, the northern arc having been affected by an amount of transport quite smaller than the southern one.

The proposed palinspastic restoration at Langhian times (Fig. 2) shows that a N versus S differentiation had also to exist during the opening of the Algero-Provençal Basin and the drifting/rotation of Corsica-Sardinia. For instance, collisional greenschist metamorphism affected the north-Apenninic units (Tuscan units) in Lower Miocene times, whilst the south-Apenninic units (San Donato and Verbicaro p.p.) were metamorphosed in post-Langhian times, probably during the early Serravallian. In addition, arc-type volcanism was absent in Corsica, while it was widespread in Sardinia.

As regards the lithosphere subducting under the northern Apennines, it had to be of thinned-continental type and rather homogeneous laterally. This lithosphere originally floored the Umbria-Marche basinal domains which were parts of the Jurassic passive margin of Tethys.

In the southern sector, markedly-different crustal and lithospheric elements had to be involved in the roll-back processes. In Langhian times, we can recognize from W to E (Fig. 2):

- domains with oceanic or extremely-thinned continental crust (Sicilide, Sannio and possibly Lagonegro domains);
- domains with thinned to normal continental crust (carbonate platforms and their margins);
- domains with thinned continental crust (north-Molise) and domains with possible oceanic crust (south-Molise - Ionian Basin).

These lithosphere inhomogeneities favoured segmentation and differential sinking accomodated by lithospheric tear faults acting as free boudaries (see Royden et al. 1987; Mantovani et al. 1992). These lateral variations across the southern sector may also account for the puzzling time/space distribution of the arc-type volcanism. Calc-alkaline volcanism was active in Sardinia from about 29 to 13 Ma (Savelli et al. 1979) and had petrochemical characters indicating NW-dipping subduction of normal oceanic lithosphere (Coulon, 1977). After a long interval of quiescence, it resumed about 2 Ma ago in Campania (Beccaluva et al. 1984), becoming widespread and important starting with 1.3 Ma in peninsular Italy and in the Aeolian Arc. The Sardinia volcanism may have reflected the subduction of the ocean-type lithosphere of the Liguride and Sicilide domains. The stop in arc-type volcanism corresponds temporally to the Sardinia collision against the western platform domains. No calc-alkaline volcanism has been found coeval with the subsequent subduction of the continental lithosphere underlying the western Apenninic platform. Arc-type magmatism resumed only when the thinned Molise crust, and the oceanic Ionian crust were involved in the subduction. These domains were located in the southern part of the study area (see Fig. 2). According to Serri (1990) and Serri et al. (1991), the Pleistocene volcanism of Italy has typical arc-type characters related to oceanic subduction only in the Aeolian Islands and Campania, whilst it becomes more and more reminiscent of continental influences moving northwards, in Latium and Tuscany.

The southern and northern domains also show marked differences in earthquake patterns. In the Northern Apennines only shallow and possibly intermediate hypocenters ($\leq$ 90 km) occur (Selvaggi and Amato 1992). The deeper hypocenters seem to depict a faint seismogenic zone deepening from the Adriatic foreland beneath the chain, in the same sense as the deflection of the continental lithosphere should have occurred. A true, though complex, Wadati-Benioff zone occurs in the Southern Tyrrhenian Sea back of Calabria, with hypocenters exceeding 450 km of depth (Anderson and Jackson, 1987). This well-delineated and narrow seismogenic slab is about 700 kilometres in lenght. According to the deformation rates calculated by Patacca et al. (1990) and taking into account Fig. 2, the slab should result from subduction processes which started before the early opening of the Tyrrhenian basin. Such a long duration may be related to the presence of wide sectors of oceanic lithosphere which dragged down intervening sectors of continental lithosphere.

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