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Crust-mantle structures and Neogene-Quaternary magmatism in Italy

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ABSTRACT After the Middle Miocene, the Tyrrhenian-Apennine region is considered a kinematically closed system. Geodynamic forces were only local, and large lateral motions, induced by plate dynamics, were absent. During the last 10 Ma these forces transformed a segment of the Alpine-Adriatic collisional belt into a deep basin and into a new mountain chain. From the analysis of geophysical and geological data we infer that mantle upwelling above a deep-seated thermal plume caused this tectonic "revolution". Support to this geological occurrence is given by the proposed presence of a 5 to 20 km-thick layer of dense magma (a soft mantle wedge, or mantle cushion) that underplates the western part of the Apennine range. This layer has contributed to the accretion of a new continental crust – an example of physical and chemical growing. The magmatic composition and the volcano-tectonic evolution indicate a tectonic rift environment and the transformation of the lithosphere mantle and crust, by a thermal anomaly and by fluid supply from deep mantle sources. In this model the high potash "Mediterranean" volcanism corresponds to the area underplated by mantle-derived material. New geophysical data acquired across the Tuscan geothermal province support this model.

1. Introduction

For the last 18 Ma the area surrounding the present Tyrrhenian Sea has been a kinematically closed system. The N-S Europe-Africa convergence rate did not exceed 7 mm/y (Olivet *et al.*, 1984), which is an order of magnitude lower than formerly considered and generally accepted convergence rate of the large plates in the Pacific ocean. With regards to the E-W directed motions, all the authors accept that the Sardinia-Corsica microcontinent was already fixed in the present position from Early Miocene. On the other side, the Adria block behaved as a microcontinent with relatively small counterclockwise rotations from Late Oligocene onward. These movements could not produce the opening of the Tyrrhenian basin, or the building of the Apennines (Anderson and Jackson, 1987a). However, the Apenninic thrust sheets underwent large displacements from west to east with associated counterclockwise rotations of up to 40°.

During the last 10 Ma, the area, previously part of the Alpine range, evolved into a deep basin and into a new mountain range. Because the low rate of plate motion does not support the existence of large scale deep subductions, formation of marginal back-arc basins and mountain building, the forces that could account for this tectonic "revolution" should be sought within the same area (Locardi, 1985). In addition, the observed parallelism of several pulses of rifting and basinal opening of the Tyrrhenian Sea, which are associated with the thrusting and the foredeep migration in the Apennines, are caused by the same geodynamic process (Patacca and Scandone, 1989).

A synthesis of all the available data supports the hypothesis of a process of mantle "swelling" at the top of a migrating thermal plume (Locardi and Nicolich, 1988). The thermal plume, migrating eastwards, is responsible for:

1) the opening of several basins and the reduction of the thickness of the lithosphere;
2) the fragmentation of the western Mediterranean into microcontinents;
3) the subsequent rotations and collisions.

This paper was presented at the GNGTS Annual Meeting dedicated to the memory of one of the authors, professor Enzo Locardi, who died ten years ago in Rome. The paper was presented at international meetings, but never published. New data acquisitions and interpretations and new evaluations of the model (Liotta *et al.*, 1998; Marson *et al.*, 1998; Scrocca *et al.*, 2003; Accaino *et al.*, 2004; Aoudia *et al.*, 2004) are providing hints that are favorable to our hypothesis, particularly in Tuscany, so it becomes necessary to commit to memory and to knowledge the work done by professor Enzo Locardi.

2. Mapping the Moho

Seismic prospections, mainly deep seismic soundings and deep seismic reflection profiles (Giese *et al.*, 1981; Liotta *et al.*, 1998; Scrocca *et al.*, 2003), combined with other geophysical observations (e.g. gravity, magnetic and heat flow data: Della Vedova *et al.*, 1991), allow us to define two distinct mantle domes, in the Tuscan-Latial area and in the South Tyrrhenian Sea, respectively [Moho map in Fig. 1; Morelli (1973); Locardi and Nicolich (1988); Nicolich and Dal Piaz (1991)]. The two domes are divided by the 41° parallel lineament (Fig. 1). These domes are uplifted by more than 50 km with respect to the neighbouring asthenosphere (Calcagnile e Panza, 1981). Volcano-tectonic and structural data confirm that these two mantle domes evolved independently and had different rates and directions of migration (Peccerillo, 1999, 2003).

After a first eastward drift, the northern dome migrated to the NE, gaining a rate of up to 2.3 cm/y, whereas the southern dome moved to the SE at a much higher rate of 6-8 cm/y (Locardi, 1985, 1986, 1988). These different migration rates and directions of the two domes can account for the different tectonic evolution between the northern and southern Apennine range.

The asthenospheric domes should not be considered simple intrusions of the asthenosphere into the lithosphere, but, to a large extent, a physical and chemical transformation of the pre-existing lithosphere, caused by heat and fluid supply from the ascending mantle plume (Locardi and Nicolich, 1988). Several authors (White and McKenzie, 1989; Griffiths and Campbell, 1991) have proposed that a high thermal regime and deep mantle supercritical aqueous fluids (mainly water and CO_2) can produce alterations in the upper mantle's physical properties (i.e., soft and hot zones).

Fig. 2 shows the mechanism of accumulation of fluids in a partly molten mass at the base of the crust. This fluidized sector acts both as lubricant and as driving force for the tectonic movements. In Fig. 2, the form of the asthenolith is taken from Suhadolc and Panza (1988) and is consistent with the convective motions denoted by:

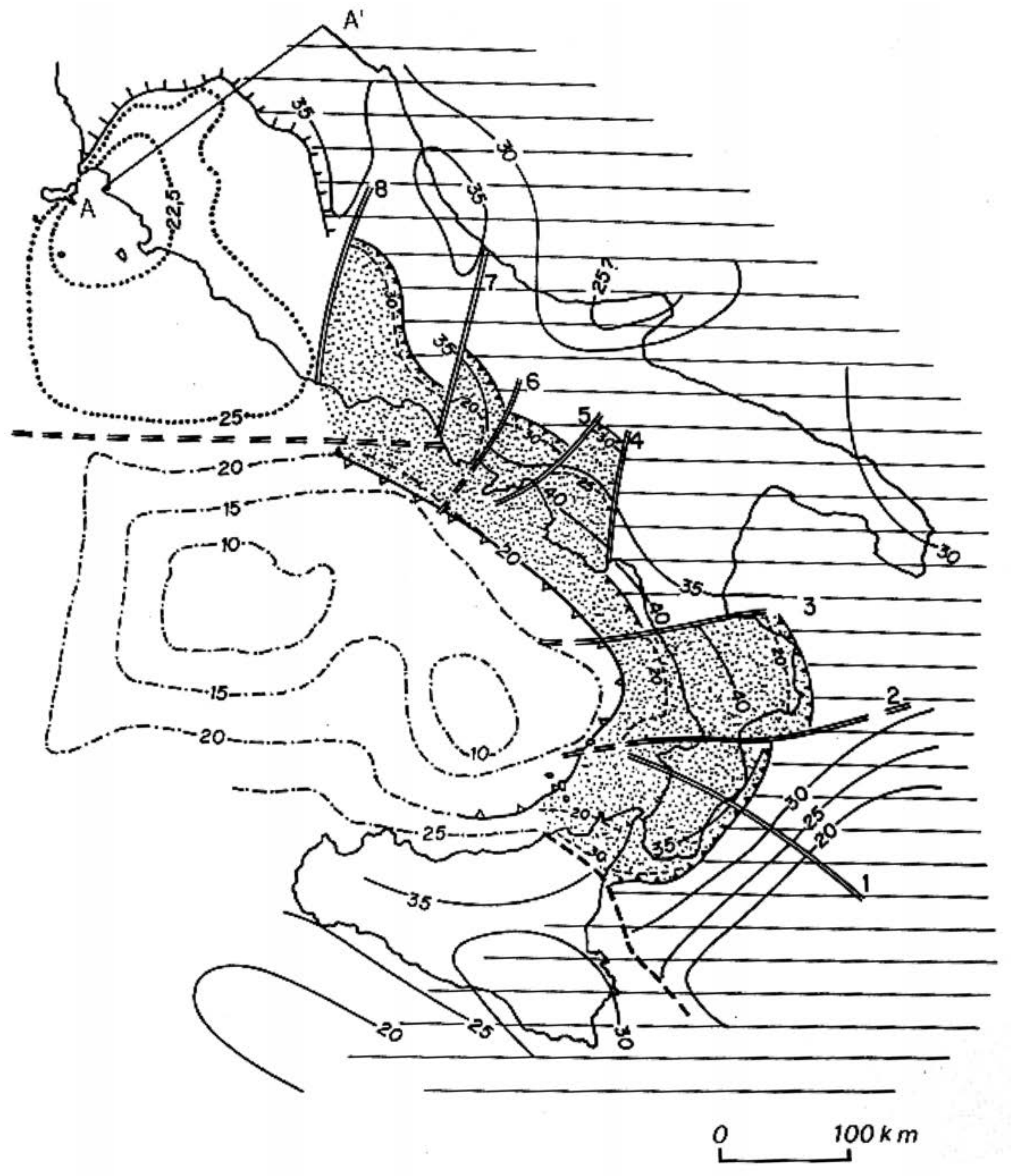
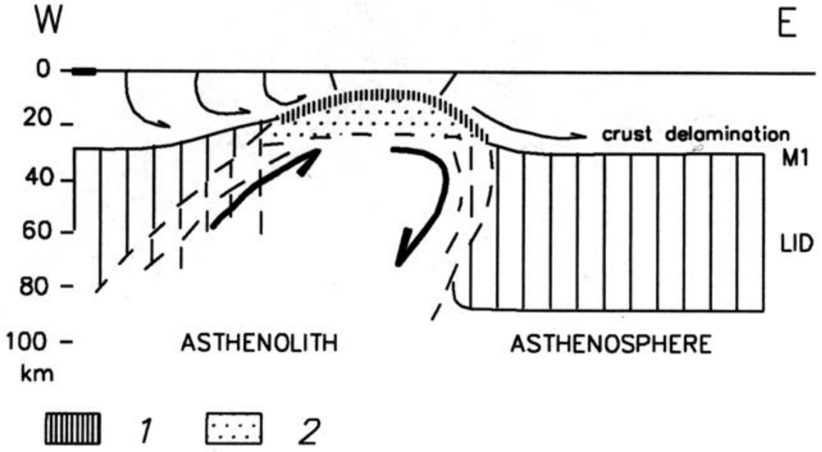


Fig. 1 - Moho isobaths map. Depths in km. The Tuscan-Latial asthenospheric dome, whose top is at a depth of about 30 km, is overlain by an 8-10 thick interval with relatively low Pn seismic velocities (7.5-7.8 km/s). The dotted lines represent the isobaths of this interval and the barbed boundary shows its steep termination against the Apennine chain. Double-dashed line (the 41° parallel lineament) separates the northern dome from the southern one. Dash-dotted lines indicate the top of the southern Tyrrhenian dome, which is more than 20 km higher than the northern one. The layer, 5-20 km thick, with seismic velocities of 7.2-7.6 km/s (dotted area with dashed isobaths), terminates sharply against the dome (line with open triangles) and its fronts are broken into blocks, which are more or less advanced and delimited by transcurrent faults (from Locardi and Nicolich, 1988): 1 = Marina di Nicotera-Gioiosa Ionica Line; 2 = Catanzaro Through Line; 3 = Sangineto-Palinuro Line; 4 = Vulture Line; 5 = Salerno Line; 6 = Napoli Line; 7 = Roccamonfina-Ortona Line; 8 = Ancona-Anzio Line. AA' trace of the sketch-section of Fig. 4.

A) ASCENDING DIAPIR



B) COLLAPSE OF THE DIAPIR'S TOP

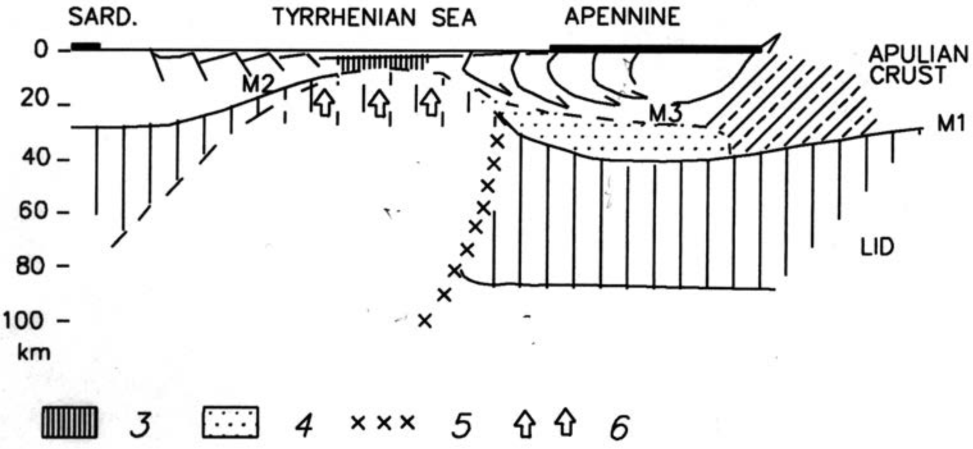


Fig. 2 - Evolutionary scheme for the asthenosphere diapir in the southern Tyrrhenian area (a W-E sketch transect, from Sardinia to Apulia). M1, M2, M3 = Adria Moho, top of the Tyrrhenian exposed mantle and the top of the mantle-derived underplated material, respectively. Thin arrows: crustal structure delamination mechanism. Thick arrows: convective movements inside the mantle. 1 = crust reduced by delamination and successively melted; 2 = zone of maximum fluids accumulation; 3 = oceanization; 4 = mantle-derived underplated material; 5 = seismic arrays corresponding to Benioff's zone of the Southern Tyrrhenian; 6 = isostatic uprising.

1) the opening of the Tyrrhenian basin;
2) the migration of the oceanized zone;
3) the volcanism;
4) the tectonic transport (Locardi and Nicolich, 1988).

The crust-mantle transition has been accurately studied and synthesized in the map shown in Fig. 2. Reference and detailed description of this map and of the related structures are presented in Locardi and Nicolich (1988). The Moho, corresponding to the thinned crust above the southern

Tyrrhenian mantle dome, is separated in the figure from the Moho of the external domains (Adria, Ionian, Sicily). A third discontinuity, revealed by the Pn of 7.2 to 7.6 km/s (Giese *et al.*, 1981; Nicolich, 1981), marks the upper boundary of a relatively low-velocity interval, 5 to 20 km thick, which underlies the base of the thinned crust and overlies the asthenospheric mantle, north of the 41° parallel lineament. However, along the eastern margin of the southern Tyrrhenian dome (dashed area in Fig. 2) the cushion is sandwiched between the Adria Moho and the Apennine crust.

We observe that the seismic velocities, that are half-way between the velocities of the mantle and those of the lower crust, are common features in continental rift zones and in ancient passive continental margins and mark the transition zone between a thinned continental and an oceanic crust (Furlong and Fountain, 1986). They are generally interpreted as underplating of heavy mafic melts extracted by a hot mantle plume (Bonatti and Seyer, 1987). Therefore, the crust-mantle transition along the western margin of the Apenninic range can no longer be interpreted as an example of crustal doubling, namely base of a wedging crust that has lost the upper mantle and part of its lower crust (e.g. Nicolich, 1981). DSS data (Ferrucci *et al.*, 1989; Nicolich and Cagnetti, 1989; Lueschen *et al.*, 1991) suggest that this interface marks the upper boundary of the material extracted from the mantle. Once found an equilibrium, the underplated material becomes part of the newly created continental crust (Sinigoi *et al.*, 1995, 2003; Dal Piaz and Martin, 1998). This model has been applied also to the Mesozoic continental-oceanic evolution of the Ionian Sea basin (Ismail-Zadeh *et al.*, 2003).

3. Mapping the volcanological data

The hypothesis of a thermal plume is consistent with the observed crust-mantle structures and the related magmatism (quantity and extreme differentiation). In a relatively limited area and in a short time interval, magmas of very different tectonic environment were effused [MORB, OIB, calcalkaline IAB, sodic to high potash undersaturated melts: Peccerillo (2003) and references herein]. In fact, all these compositions are generally found in melts extracted above ascending thermal plumes of a deep mantle origin (McKenzie and Birckle, 1988; Campbell and Griffiths, 1990).

Fig. 3, summarizes the interesting relationship between the deep structures and the volcanic evolution and composition of the area. The 41° parallel lineament, dividing the two mantle uplifts, separates two distinct mantle domains: crustal anatectic and high potash ("Mediterranean") to the north; tholeiitic, alkali basalts and calcalkaline-shoshonitic series to the south.

In both mantle uplifts, the magma formation was induced by heat and mantle metasomatic fluid supply (Locardi, 1985). However, the two magmatic domains evolved differently as discussed in the following.

In the northern dome, we observe an eastward drift of the eruptive axes, since the Tortonian age, followed by a counterclockwise rotation and emplacement into its final position by the Pleistocene (0.6 Ma axe in Fig. 3). Peccerillo (2003) is proposing age intervals spanning from 12-14 Ma to the west to 0.2-0.1 Ma to the east). The almost contemporaneous magmatic activity along single eruptive axes, hundreds of kilometres long, is another feature of the northern region.

In the same area (southern Tuscany, Latium, Campania), the high potash “Mediterranean” volcanism erupted along an inland arc of about a 450 km length [Fig. 3 and Locardi (1988)], when the Apenninic structure was already emplaced and its strong tectonic diversification along the range had already occurred. The eruption began almost contemporaneously 0.8-0.6 Ma ago and can be considered presently active and along the whole arc.

We infer a link between crustal anatectic and high potash mantle magmatism from the following two observations. First, the crustal anatectic rocks are strongly enriched in those LIL elements whose abundance characterizes the high potash magmatism. Secondly, the crustal rocks contain inclusions and intrusive bodies of mantle lamproites (Peccerillo and Manetti, 1985; Serri

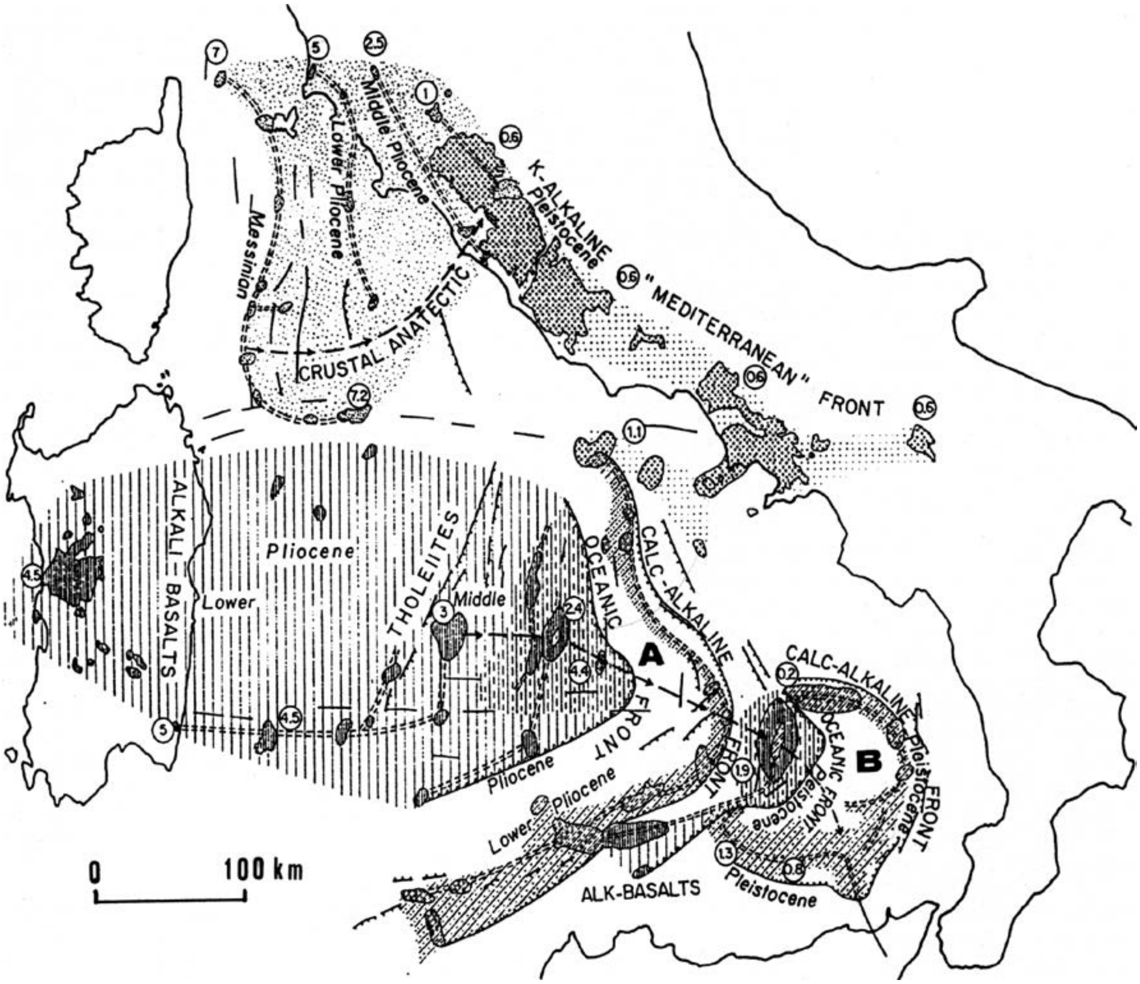


Fig. 3 - Map of the Neogene-Quaternary magmatism [part of the data from C.N.R. (1989)]. Crustal anatectic magmatic domain (light stipples); high-potash-“Mediterranean”-magmatic domain (heavy stipples); tholeiitic and alkali-basaltic domain (vertical lines); oceanized areas (vertical full and dashed lines); calcalkaline-shoshonitic magmatic domain (oblique lines with stipples). Encircled numbers indicate the ages of the effusions in Ma (Fornasieri, 1985a, 1985b; Villa, 1991, personal comm.). Thick arrows show the drift direction of the thermal plumes. Double dashed lines indicate the main eruptive axes.

et al., 1993). This implies that the crust was molten above the migrating mantle dome where CO_2-dominated fluids exhaling from the mantle were accumulated. In this regard, several petrologists propose [Crisci *et al.* (1991) and reference herein] a metasomatized mantle as the source of the high potash melts in Italy. However, the high potash volcanism should correspond only to the area underplated by the heavy mantle material. Therefore, we suggest a generic link between the potassic magmatism and the underplated material.

In the southern dome, because of the stronger tectonic extension and the very pronounced crustal thinning, the decompression melting effect is added and the volcano-tectonic pattern and the magmatic composition are quite different. Volcanism started in late Messinian near the coasts of Sardinia, after the northern dome, and became progressively younger eastwards. This movement of the thermal plume is reflected by the distribution of the oceanized areas and by the magmatic types.

A first oceanized area was formed 4-5 Ma ago in the Vavilov basin (A in Fig. 3). Approximately 2 Ma ago it spread towards the southeast and most likely rotated clockwise in the Marsili basin (B in Fig. 3). Tholeiitic basalts dominate both oceanized basins (Vavilov and Marsili). In these basins, on the back of the southeastward advancing thermal front, the magma became alkali-olivine basaltic. Conversely, a parallel belt of calcalkaline-shoshonitic volcanoes formed on the front of the oceanized zones (Fig. 3). The effusion age of these main magmatic types is nearly contemporaneous for both basins, A and B, and happened respectively at 5 and 2 Ma ago. Therefore, we suggest that tholeiite-alkali basalts and the calcalkaline magma formation in this zone are connected.

The tholeiite-alkali basalt association is generally explained as an effect of a different degree of partial melting (Campbell and Griffiths, 1990). We recognize that this is consistent with the different tectonic extensions found in the Tyrrhenian basin (i.e., with decompression in correspondence of oceanized areas, Fig. 3).

The neighbouring calcalkaline volcanism is usually associated with subduction-related magmas. However, in our case, there are no recent active subductions (Patacca and Scandone, 1989). In addition we observe that the alkaline belt is found only at the front of the advancing thermal plume, and its time duration is short (1 Ma). Petrological studies (Foley and Wheller, 1990; Kelemen *et al.*, 1990) have also shown that the calcalkaline character, rather than being diagnostic of subduction, depends on the presence of fluids and on the low rate of magma separation and ascension in the mantle. A calcalkaline character in magmas can also be produced by the reaction of Magnesium tholeiite and depleted peridotite in presence of fluids. Our data suggest that these conditions were present on the advancing front of the thermal plume, while it was migrating into new portions of the cold lithosphere of the external domains (see the mechanism in Fig. 2).

The new deep seismic reflection data, recorded across the geothermal province of southern Tuscany [CROP-03 and CROP-18 profiles: Liotta *et al.* (1998); Marson *et al.* (1998)], are of great interest. The base of the crust was detectable at 7.5-8 s TWT, consequently at a 22-23 km depth, which is in agreement with the refraction data (DSS) acquired in the area (Giese *et al.*, 1981) and with reflection data acquired offshore in the Tuscan archipelago (Mauffret *et al.*, 1999). The crust-mantle transition is marked in the seismic images by high-amplitude continuous, fairly thick, reflecting intervals. Somewhere, they are interrupted by marked tectonic deformations related to the magmatic production and mafic intrusions. The rising of hot melts from below, with unstable equilibrium among rock properties, temperatures, fluid pressures, and confining pressures at different levels of the crust was stated in the Tuscan geothermal province from the integrated analysis of the seismic data (Accaino *et al.*, 2004). The interpretations, supported by seismic prospecting methods different both for penetration and resolution, have confirmed that the lithosphere of the southern Tuscany is interested by strong velocity and density changes.

The seismic transects confirmed the presence of high-amplitude reflectors within the middle and lower crust. The presence of trapped fluids can explain the reflectivity in the upper crust. The reflectivity associated to lithologic changes in the middle crust can be explained by the presence of magmatic intrusions into the extended deep continental crust. The intrusion of mantle-derived magmas is commonly referred to as magmatic underplating and has been studied by Sinigoi *et al.* (1995) along the considerable outcroppings of lower crust bodies in the Ivrea-Verbano zone (southern Alps in NW Italy). The heat released at the base of the crust induced anatexis in the overlying crustal rocks with production of granitoid melts, quickly migrating towards higher crustal levels, leaving behind progressively depleted restites, the residual product of the fusion

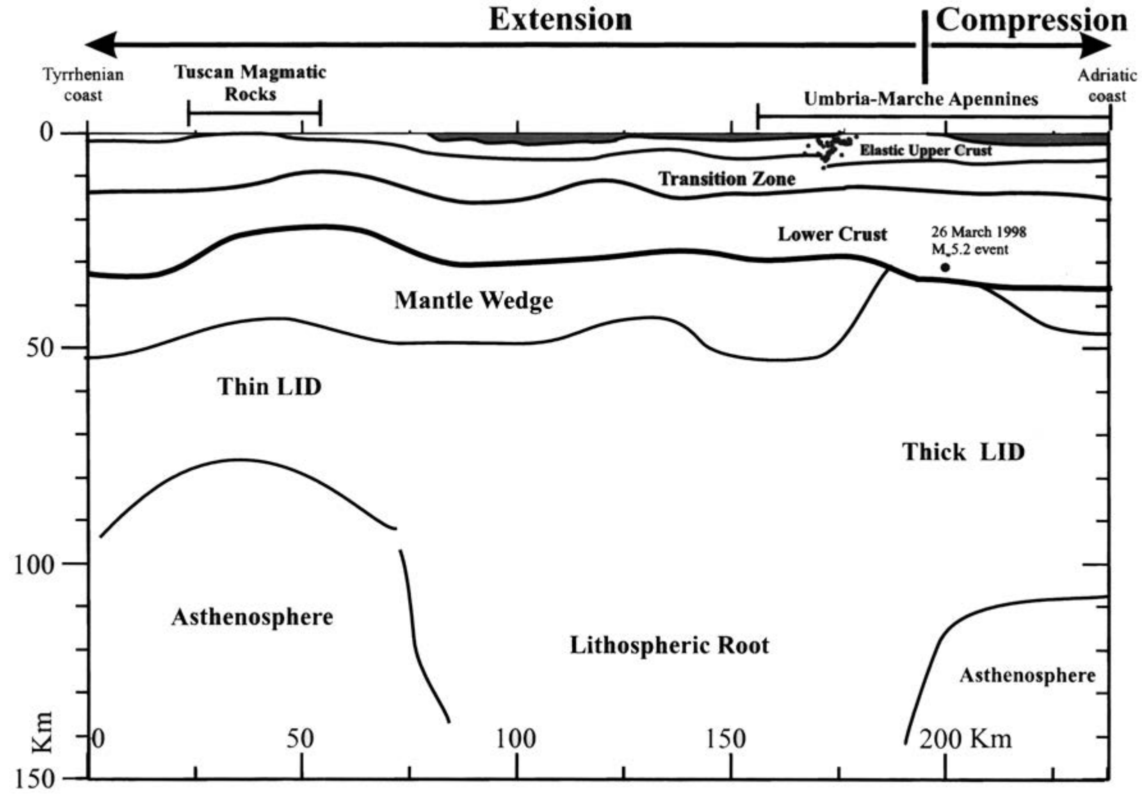


Fig. 4 - Sketch of the lithosphere-asthenosphere system beneath Tuscany and Umbria-Marche, from the Tyrrhenian to the Adriatic Sea following the CROP-03 transect [trace A-A' in Fig. 1; from Chimera *et al.* (2003)]: the Tuscan mantle dome.

processes, representing high-grade metamorphic and refractory rocks. A sharp distinction between denser materials and less dense anatectic melts and metamorphosed volcano-sedimentary rocks can be the end result. The combination at different depths of the distinct products of the above process can justify the presence of variations of the impedance and of the observed reflectivity (Accaino *et al.*, 2004).

Aoudia *et al.* (2004) inspected the lithosphere-asthenosphere system with new shallow and deep tomographic inversion studies of surface waves, integrating the deep P-wave seismic refraction (DSS) and reflection profiling crossing the Tuscan geothermal and metamorphic complex and the Umbria-Marche geological domain, towards the Adriatic foreland. Lithosphere roots, more than 100 km wide, have been revealed between the Tuscan Geothermal Province and the Umbria-Marche domain and a sharp and well-developed low velocity zone in the uppermost mantle, dying out progressively from the Tyrrhenian towards the east beneath the Apennines, separates the crust and lid in the sketch model in Fig. 4. This cushion (soft mantle wedge) is nearly 20 km wide, whereas the large lithospheric roots, inferred to be delaminated lid material, have been interpreted as the remnant portions of the old Adriatic-Alpine slab. The high heat flow values (Della Vedova *et al.*, 2001) correspond to the extension of the mantle wedge and are in agreement with an upward flow field, suggesting that the mantle wedge is partially molten. The partial melting of the uppermost mantle and the delamination processes are accepted from Serri *et al.* (1993), when considering the magmatism of the northern Apennine arc, but they prefer to relate it to the subduction processes of the Adriatic continental lithosphere (Doglioni *et al.*, 1999).

Conclusions

The formation of the Tyrrhenian basin and the formation and evolution of the Apennines are the effect of two asthenospheric mantle domes. These domes cannot be interpreted as simple intrusions of the asthenosphere into the lithosphere, but they should be considered the result of the interaction between the pre-existing lithospheric mantle (and crust) with a thermal input in presence of fluids derived from deep mantle sources. Magma is produced at the top of the ascending mantle plume and is accreted at the base of the crust-underplating or continental crust accretion in a rift tectonic environment.

This model does not support the existence of active subduction zones set off by external convergence forces. However, existence of a seismically active belt in the southern Apennines is indisputable [Anderson and Jackson (1987b); Valensise *et al.* (2004) and references therein]. The currently active seismic zone coincides with the front of the convective cell associated with a hot asthenolith and the opposing mantle (Fig. 2). Motion of a hot mass may induce stresses and seismic activity at the interface with the neighbouring cooler mantle (see Fig. 2). In order to explain the deep seismic activity, we propose considering in this scenario other processes, such as mineralogical phase transformations with implosive transition from olivine to spinel and to oxide (Frohlich, 1989; Green and Burnley, 1989), stresses induced by the presence of fluids and by the consequent variation of the hydrostatic pressure, shear stress and temperature contrasts.

Our geodynamic model is supported by the presence of a low-velocity, partially molten mantle wedge, that has been demonstrated by surface wave analyses in southern Tuscany (Fig. 4). In this area, we observe much lower migration rates and we have indicated the northern asthenosphere dome with a different tectonic evolution with respect to the southern Tyrrhenian domain. For the seismicity of the area, buoyancy-driven deformations have been considered in the northern dome as the prevailing mechanism, which could explain the juxtaposed crustal contraction and extension and also the distribution of intermediate depth earthquakes (Aoudia *et al.*, 2002, 2004). In addition, the intrusion of mantle derived magmas and fluids dominate the crust of southern Tuscany and represent the source and motor of the geothermal province. Moreover, we propose that a similar mechanism has affected also the southern Tyrrhenian eastern margin and has controlled the Southern Apennine chain evolution.

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