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STRUCTURAL FEATURES OF SOUTHERN TUSCANY, ITALY

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ABSTRACT

The main structural features of Southern Tuscany are the result of post-collisional extensional tectonics which have affected the inner part of the Northern Apennines since the Early-Middle Miocene. Geological analyses have shown that several deformational events are related to the development of extensional tectonics. Geophysical studies suggest that a kinematically active mid-crustal shear zone is located at the present rheological boundary between the upper part of the crust, mainly characterized by brittle deformation, and the lower part, mainly characterized by ductile deformation. The coexistence of extension with the compression tectonics, which affected the outer zone of the Northern Apennines, is explained as a result of the post-collisional evolution.

INTRODUCTION

Tuscany is located in the inner part of the Northern Apennines (Fig. 1) and its structural setting is a consequence of two contrasting processes: the first related to the convergence and collision (Boccaletti and Guazzone, 1972; Boccaletti et al., 1981) of the Adria Plate and the European Plate, represented by the eastern Corsica margin (Late Cretaceous-Late Oligocene, ?Early Miocene); the second related to the extensional tectonics which have been acting since the Early-Middle Miocene (Carmignani and Kligfield, 1990; Jolivet et al., 1990; Bertini et al., 1991; Baldi et al., 1994b; Carmignani et al., 1994; Carmignani et al., 1995). This extension migrated eastwards, affecting the entire inner part of the Northern Apennines: the opening of the Northern Tyrrhenian Basin is the main evidence of this extensional tectonics (Carmignani et al., 1994).

Extension resulted in development of northern and southern tectonic sectors in Tuscany which are separated by a SW-NE trending lineament ("Livorno-Sillaro" Line, Bortolotti, 1966) of lithospheric significance (Royden et al., 1987). They exhibit contrasting extension, which is greater in the southern sector, i.e. the Southern Tuscany.

Southern Tuscany is characterized by an average altitude of 270 meters, positive Bouguer anomalies (Elter et al., 1975; Giese et al., 1981) and high heat flow: 120

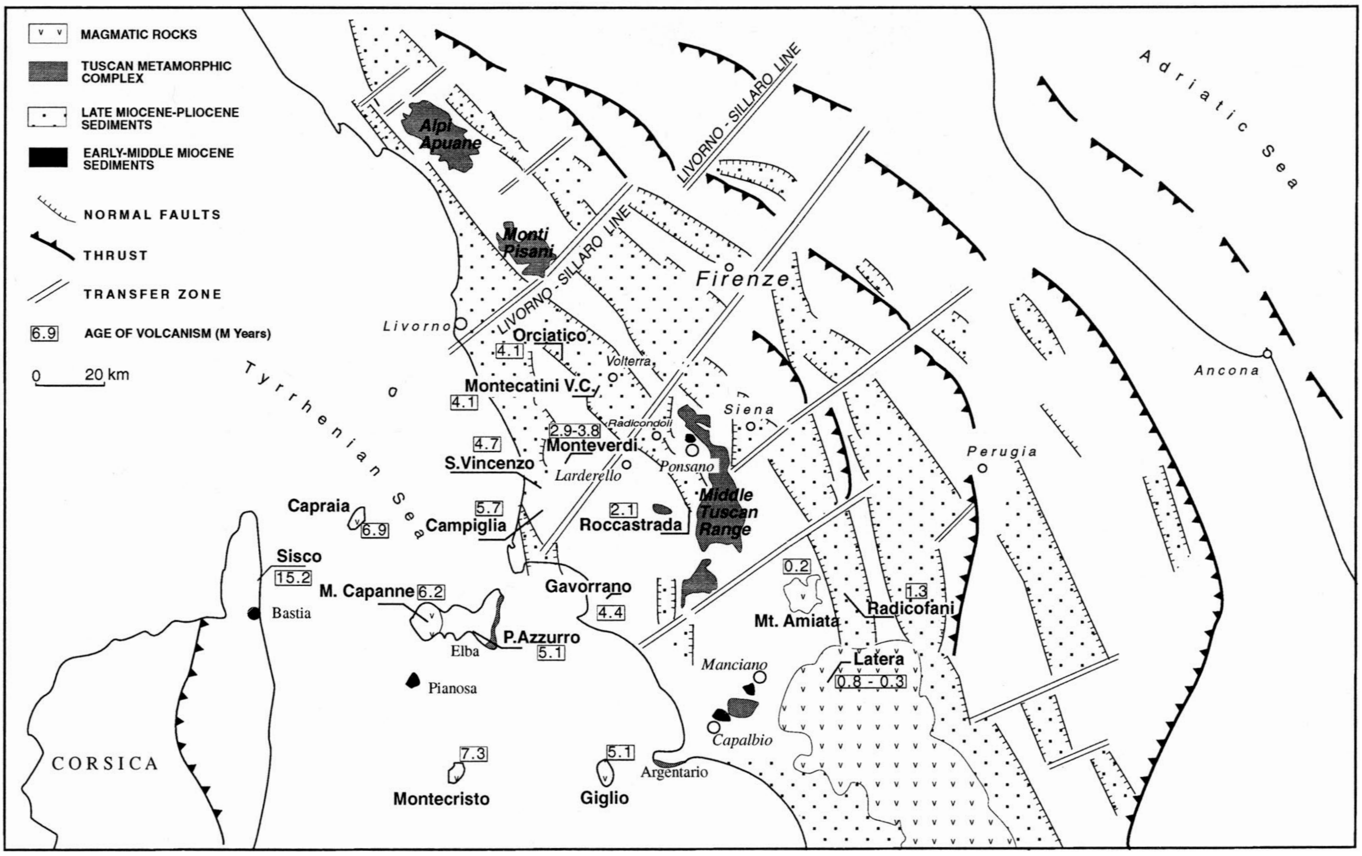

Fig. 1 - Sketch map of the Northern Apennines showing the main structural features.

mW/m^2 on the average, (Fig. 2) with local peaks (e.g., Larderello geothermal field) up to 1000 mW/m^2 (Mongelli et al.,1989; Mongelli and Zito, 1991). Present crustal and lithospheric thicknesses of Southern Tucany are estimated to be about 22 km and 30 km, respectively (Calcagnile and Panza, 1981; Locardi and Nicolich, 1992; Decandia et al., 1998).

Extension in the inner zone of the Northern Apennines is coeval with the development of compressional structures and foredeep basins in the outer zone. Extension and compression have been migrating eastwards since the Early-Middle Miocene.

Topics of discussion will be the main crustal structures of Southern Tuscany and the geodynamic environment in which these structures could have developed.

PALEOGEOGRAPHIC DOMAINS

The Northern Apennines orogenesis created a nappe belt which derived from the deformation and stacking of several paleogeographic domains (Fig. 3). From the top they are:

1) The Ligurian Domain, an oceanic domain made up of Jurassic ophiolites and related Jurassic-Lower Cretaceous cover, overlain by Cretaceous-Eocene terrigenous flysches.
2) The Sub-Ligurian Domain represents the transitional area between the oceanic crust of the Ligurian Domain and the continental crust of the Tuscan Domain. It is made up of a terrigenous sedimentary sequence of Late Cretaceous-Oligocene age.
   The tectonic units derived from the Ligurian and the Sub-Ligurian Domains were stacked within an accretionary wedge during the Late Cretaceous-Eocene (Treves, 1984; Principi and Treves, 1984). They later overthrust the Adria continental margin in the Late Oligocene-?Early Miocene.
3) The Tuscan Domain is made up of continental sequences which were deformed at different crustal levels and can be divided into two sub-domains.
   (a) The Internal Tuscan sub-Domain, from which the Tuscan Nappe derived. This sub-Domain is made up of sedimentary rocks, from the bottom of the sequence they are: Upper Triassic evaporites, Lower Jurassic-Lower Cretaceous carbonatic sequence, an Lower Cretaceous-Oligocene carbonatic and clayey sedimentary sequence and a Upper Oligocene-?Lower Miocene terrigenous flysch. Some Authors (Tongiorgi, 1978; Dallan Nardi and Nardi, 1978; Boccaletti et al., 1981) proposed that the sub-Domain of the Tuscan Nappe was located close to the Umbro-Marchean Domain, in a more external location. During the Late Oligocene-?Early Miocene, the Tuscan Nappe with the Ligurian Units already thrust over its top, was detached along the Upper Triassic evaporitic level and thrust over the
   (b) External Tuscan sub-Domain (Tuscan Metamorphic Complex), presently made up of green-schist metamorphic rocks related to the Paleozoic-Tertiary formations. Lower-Middle Triassic "Verrucano" lithotypes (mainly quartzites and phyllites) are included in this sub-Domain. Rocks from this sub-Domain crop out in the Alpi Apuane core complex, in the Monti Pisani and in the Middle Tuscan Range (Fig. 1). The Tuscan metamorphic Complex has been investigated through deep wells in Southern Tuscany. It consists of three metamorphic groups: i- a Mesozoic-Paleozoic Group, including quartz meta-conglomerates, quartzites and phyllite (Verrucano Group, Middle-Early Triassic), sandstone, phyllite (Middle-Late Carboniferous-Early Permian); these rocks are involved in duplex structures and they crop out extensively along the Middle

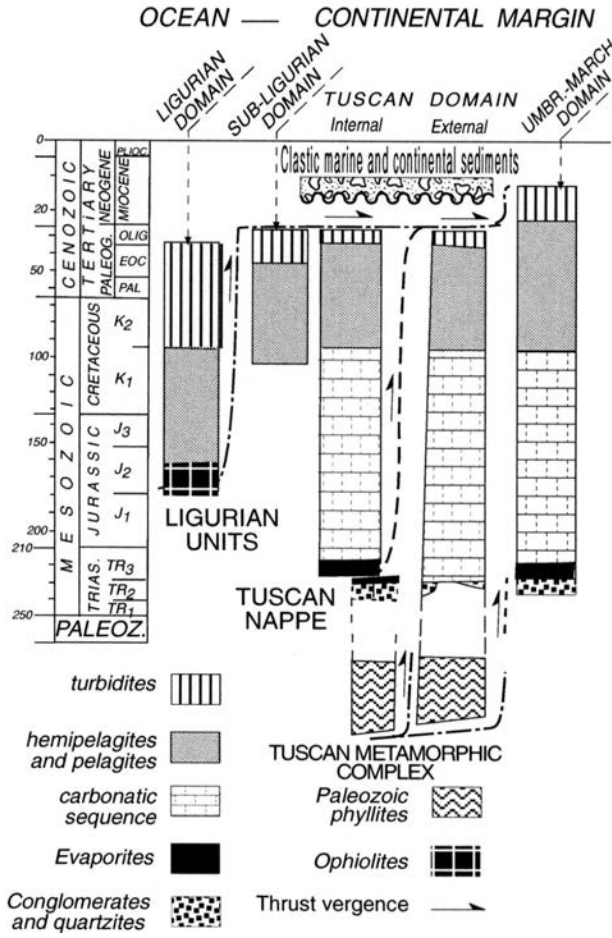

Fig. 3 - Relationship between stratigraphic and tectonic units of the Northern Apennines (after Carmignani et al., 1994, modified).

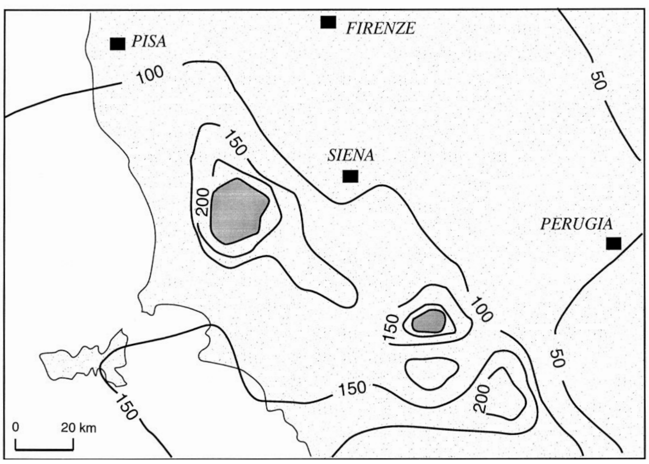

Fig. 2 - Simplified heat flow map of Southern Tuscany. Contour lines are in mW/m^2. Grey areas indicate the Larderello area, to the North, and the Monte Amiata area, to the South. (after Mongelli et al., 1989 and Mongelli and Zito, 1991, modified).

Tuscan Range (Costantini et al., 1988); ii- a Phyllite-quartzite Group; and iii- a Hercynian Micaschist Group. The phyllite-quartzite Group and the Micaschist Group were derived from Silurian-Devonian protoliths (Puxeddu, 1984; Elter and Pandeli, 1990). These three groups, affected by Alpine greenschist metamorphism (Elter and Pandeli, 1990), were referred to as the Monticiano Roccastrada tectonic Unit (Bertini et al., 1991).

4) The Umbro-Marchean Domain consists of continental margin deposits made up of Permian-Triassic "Verrucano" (reached by borehole), Upper Triassic evaporites, Lower Jurassic-Eocene carbonatic sequence, Eocene-Pliocene terrigeneous sequence. This Domain, which does not crop out in Southern Tuscany, constitutes the more external zone of the Northern Apennines. Here the Neogene deformation formed a fold and thrust belt above a detachment level located within the Upper Triassic evaporites (Baldacci et al., 1967; Tavarnelli, 1997, with ref. therein).

Deep boreholes in Southern Tuscany reached a Gneiss Complex, under the Monticiano Roccastrada Unit, i.e. the Tuscan Metamorphic Complex. The Monticiano-Roccastrada Unit and the Gneiss Complex are separated by a ductile shear zone, related to the Late Oligocene-?Early Miocene compressional stage. In contrast to the Monticiano-Roccastrada Unit, the effects of the Apennine orogeny are not recorded in the Gneiss Complex. The Gneiss Complex is therefore considered part of the Adria continental crust which was not involved in the Northern Apennine orogeny (Elter and Pandeli, 1990). It may correspond to the Apennine foreland crust (Bertini et al., 1991). In the phyllites and in the micaschists of the Monticiano-Roccastrada Unit and in the Gneiss Complex drilled in the Larderello area, a later static high temperature/low pressure metamorphism was superimposed on previous mineral associations (Del Moro et al., 1982; Puxeddu, 1984). Studies of borehole petrology have recognized HT/LP conditions in rocks recovered from up to 2000 meters (Del Moro et al., 1982; Villa and Puxeddu, 1994).

PALEOGENE COMPRESSIONAL FEATURES

Compressional structures have been thoroughly investigated in the tectonic window of the Alpi Apuane core complex, located in northern Tuscany. Here metamorphic rocks of the External Tuscan Domain and Paleozoic phyllites crop out extensively.

In the Alpi Apuane region, compressional tectonics determined large recumbent isoclinal folds (Carmignani and Kligfield, 1990). The axial plane schistosity is characterized by greenschist metamorphism (± biotite). The age of this compressional event is dated at 27 Ma (Kligfield et al., 1986); this result agrees with the biostratigraphic data (Dallan Nardi, 1977) of the youngest metamorphic formation and of the overthrusting of the Ligurides onto the Tuscan Domain.

In Southern Tuscany (Middle Tuscan Range and Monte Argentario), recent petrographic studies of the exposed Verrucano lithologies, have recognized a mineral assemblage (± magnesiocarpholite) indicating high pressure/low temperature metamorphic conditions (Theye and Reinhardt, 1994; Giorgetti et al., 1998).

NEOGENE EXTENSIONAL FEATURES

After the tectonic emplacement of the Monticiano-Roccastrada Unit (Late Oligocene-?Early Miocene), three main extensional events affected Southern Tuscany. This extension profoundly modified the geometric relationships between the tectonic units.

First extensional event

Three examples of geological sections through the area affected by this extensional event are shown in Fig. 4. Here the highest structural units in the nappe succession, the Ligurides, directly overlie either the Upper Triassic evaporites or the Verrucano Group: thus the Tuscan Jurassic-Oligocene lithologies are missing. The omission of stratigraphic portions is the most common tectonic feature of Southern Tuscany. This structural condition, known as "serie ridotta" (= reduced sequence) (Signorini, 1949; Trevisan, 1955; Giannini et al., 1971; Lavecchia et al., 1984; Bertini et al. 1991; Decandia et al., 1993), resulted from extensional faults characterized by two main flats: the first is located at the base of, or within, the Ligurides, and the second at the base, or within, the Upper Triassic evaporite level. These flats are connected by a ramp which dissects the carbonate and terrigeneous sequence of the Tuscan Nappe. Other secondary flats occur inside the less competent layers of the Ligurides and the Tuscan Nappe. A stretching value of more than 60% over a distance of 98 km has been estimated for this first extensional event (Bertini et al., 1991).

Both in southern and in northern Tuscany (i.e.: the Alpi Apuane core complex, Carmignani and Kligfield, 1990), the Upper Triassic evaporite level represents the main detachment level which divides an upper plate characterized by brittle deformation from a lower plate characterized by coeval mainly ductile deformation (Bertini et al., 1991; Carmignani et al., 1994).

In the Alpi Apuane core complex, the ductile extensional deformation produced folds ranging from kilometric to centimetric dimensions (Carmignani and Kligfield, 1990), crenulation schistosity and NW-SE intersection lineations. These structures deformed the older Oligocene collisional ones. Chloritoid and kianite are syn-tectonic with the beginning of the Alpi Apuane extensional event, thus suggesting that the thermal acme was coeval with extension (Franceschelli et al., 1986; Carmignani et al., 1994). Phengite and chlorite crystallized during this event. K-Ar and $^{40}Ar/^{39}Ar$ age determinations, conducted on white micas, indicate 12-14 Ma (Giglia and Radicati, 1970; Kligfield et al., 1986), suggesting that extension was already active during the Middle Miocene. Exhumation of the Alpi Apuane core complex is related to this time period (Carmignani and Kligfield, 1990).

In Southern Tuscany marine sediments were deposited discordantly on the Ligurian Units, after the "serie ridotta" (= reduced sequence) extensional event. This first extensional event is related to the Burdigalian-Langhian period on the basis of stratigraphic considerations (Baldi et al., 1994b; Carmignani et al., 1994; Carmignani et al., 1995) and mineral cooling ages of the Alpi Apuane core complex (Carmignani et al., 1995). This event migrated eastwards to the central part of the Northern Apennines (Perugia area) where Serravallian-Tortonian terrigeneous deposits (Marnoso-Arenacea Formation) rest tectonically on Upper Triassic limestone (Dessau, 1962; Ghelardoni, 1962).

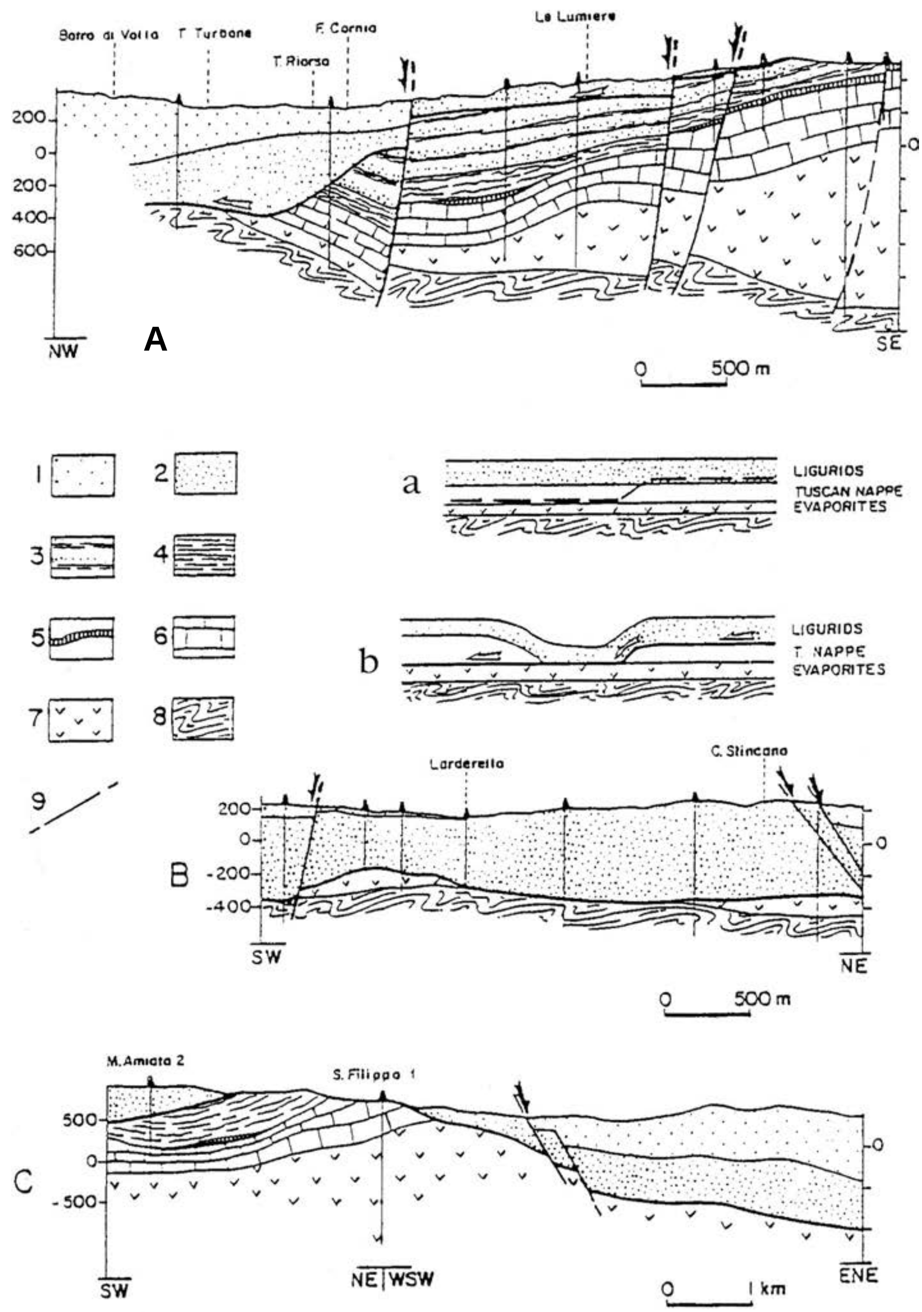

Fig. 4 - Three examples of geological cross sections through the area of the "serie ridotta" (= reduced sequence) in Southern Tuscany. A) Cross section through the Larderello zone (see also Fig. 1). The structures related to the two extensional events which determined the structural setting of Tuscany are shown. The first extensional event produced stair-case normal faults with two main flats located at the base of the Ligurian Units and within the Upper Triassic evaporites, respectively. These flats are connected by a ramp which dissects all of the Tuscan Nappe. These structures are dissected by younger generations of normal faults which now border the main Miocene and Pliocene basins (after Lazzarotto, 1967; modified). a-b) Simplified sketch of the geometry of the tectonic surfaces which produced the "serie ridotta" (= reduced sequence). B) Cross section through the Larderello area. The Ligurian Units lie directly on the Tuscan Metamorphic Complex and, locally, on the Upper Triassic evaporites. The Tuscan Nappe is omitted in this example (after Mazzanti, 1966; modified). C) Cross section of the eastern Amiata area showing the structures described above (see also Fig. 1 - after Calamai et al., 1970; modified). Symbols: 1- Miocene and Pliocene clastic sediments. 2- Ligurian Units (Middle Jurassic-Eocene). Tuscan Nappe: 3- Upper Oligocene-?Lower Miocene arenaceous flysch; 4- Cretaceous-Oligocene marlstones and pelagic limestones; 5- Upper Jurassic cherts; 6- Jurassic limestones; 7- Upper Triassic evaporites. 8- Tuscan Metamorphic Complex. 9- normal faults. White arrows: direction of displacement along the normal faults related to the first extensional event. Black arrows: direction of displacement along the normal faults which dissect the previous extensional structures (from Carmignani et al., 1994, modified).

Second extensional event

A new generation of normal faults is recognized in Southern Tuscany (Baldi et al., 1994b). These faults, which dissect all the older structures, tend to flatten in the Paleozoic phyllites, under the Verrucano Group (Fig. 5). This extensional event caused the stratigraphic omission of the Verrucano Group, the superimposition of either the Ligurides or the Upper Triassic evaporites on the phyllites and the asymmetrical mega-boudinage of the rocks belonging to the Verrucano Group (Bertini et al., 1991; Carmignani et al., 1994).

The second extensional event occurred in a period between the Serravallian and the late Messinian (Baldi et al., 1994b). Lacustrine and marine sedimentation took place in the tectonic depressions which developed in this time span. The best examples are from the Radicondoli and Volterra basins (Mazzanti, 1966; Lazzarotto and Mazzanti, 1978; Baldi et al., 1994b; Testa, 1995) where the upper Tortonian-upper Messinian sediments are more than 1000 m thick at the center of the basins. These Miocene sediments are folded and are characterized by intra-formational unconformities (Bernini et al., 1990; Boccaletti et al., 1992; Boccaletti et al. 1996) probably related to the stair-case geometry of syn-sedimentary normal faults. Uplift events occurred in the framework of the Neogene extensional tectonics (Baldi et al., 1994b).

Third extensional event

This event is characterized by NNW-SSE and N-S oriented normal faults. These faults dissect all the previous structures, including the Upper Triassic evaporite and phyllite detachment levels. A "horst and graben-type" structure is related to this third extensional event (Figs. 1 and 5). In

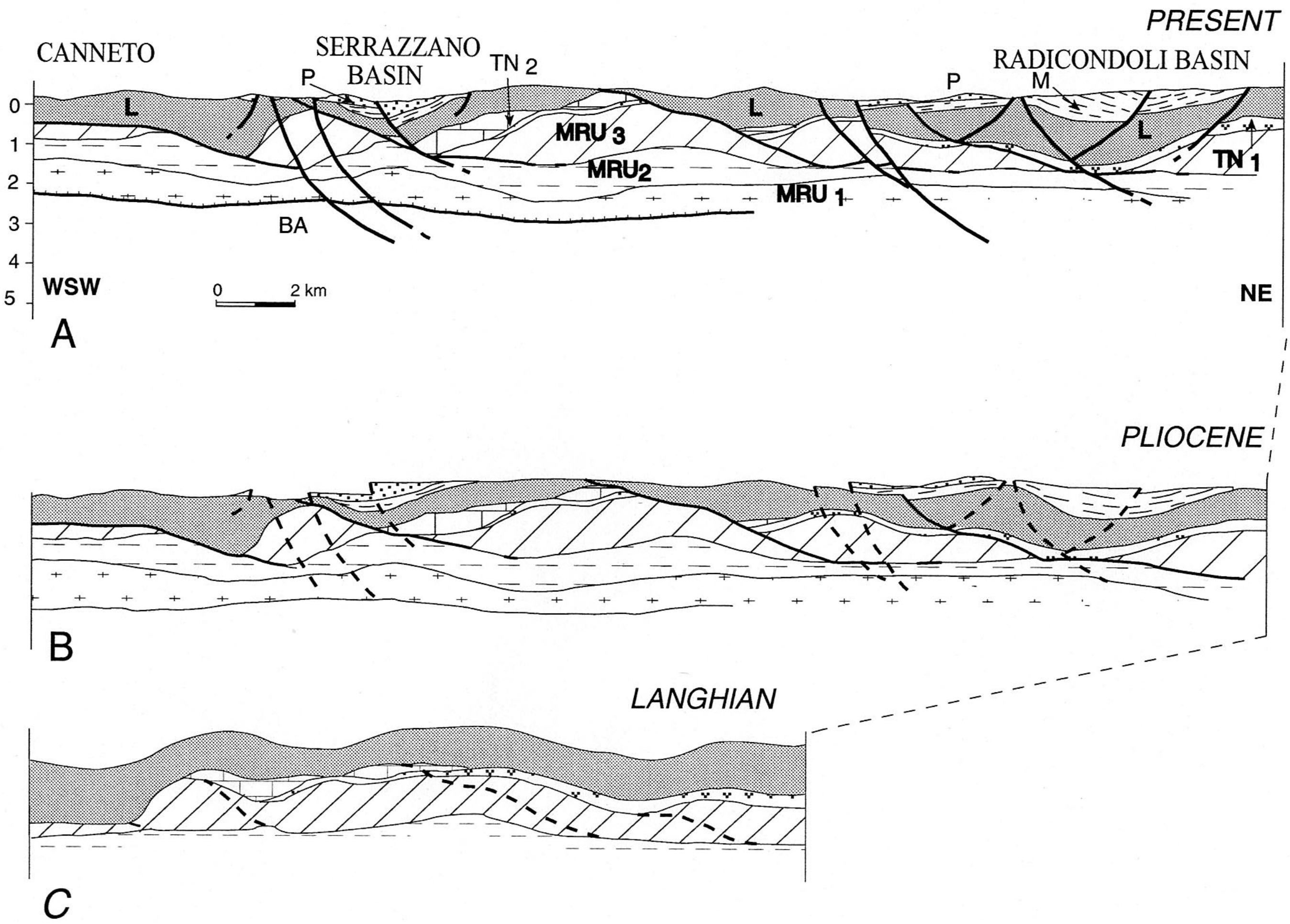

Fig. 5 - A. Geological cross section through the Larderello geothermal field (constructed from borehole stratigraphy, seismic reflection lines and field mapping). Pliocene normal faults crosscut all earlier structures: P- Pliocene sediments; M - Upper Miocene sediments; L- Ligurian Complex. Tuscan Nappe (TN): TN_2- carbonatic and terrigenous sequence (Jurassic-Late Oligocene-?Early Miocene); TN_1- Upper Triassic evaporites. Monticiano Roccastrada Unit (MRU): MRU_3- Mesozoic-Paleozoic Group; MRU_2- phyllite-quartzite Group; MRU_1- Hercynian micaschist Group; BA- Gneiss Complex.
B. Reconstructed Pliocene geological section. Note that Upper Miocene sediments are preserved in tectonic depressions defined by synsedimentary normal faults related to the second extensional event; Lower and Middle Pliocene sediments rest unconformably on Upper Miocene sediments which were deformed during deposition. During the second extensional event, the deepest rocks were exhumed.
C. Reconstructed Langhian geological section assuming that kinematic indicators did not change direction during post-collisional extensional tectonics. The restoration assumes no change in bed length in the MRU_3 Group or in the carbonate and terrigenous part of the Tuscan Complex. No change in bed volume is assumed in the Ligurian complex, in the Triassic evaporites or in the MRU_2 and MRU_1 Groups (after Baldi et al., 1994b).

Early Pliocene, marine sediments were deposited in these tectonic depressions; Middle Pliocene marine sediments were mostly deposited after a short period of uplift and erosion (Bossio et al., 1993). The main tectonic depressions are dissected by SW-NE transfer zones (Bartolini et al., 1983; Liotta 1991). The stretching caused by this Pliocene extensional event is estimated to about 6-7% over a distance of 98 km (Bertini et al., 1991).

SEISMIC REFLECTION STUDIES

The seismic reflection lines, mainly acquired during explorations for geothermal sources in the Larderello and Amiata regions, show an upper part characterized by low reflectivity and a lower part characterized by high reflectivity (Cameli et al., 1993). The top of the lower part is marked by a discontinuous reflector of high amplitude, referred to as the K-horizon (Batini et al., 1978), which has local bright spot features (Batini et al., 1985). The K-horizon often bounds a facies with strong convergent and divergent reflections and lozenge shaped geometry (Fig. 6). In the Larderello area, normal faults of the third extensional event tend to flatten either in the K-horizon or inside the lozenge-shaped facies (Bertini et al., 1991; Baldi et al., 1994b; Cameli et al. 1993; 1998).

Most local earthquakes (Fig. 7) are located in the lozenge-shaped facies which is at a depth of 4-6 km, in the Larderello and Amiata areas. In addition, the hypocentral events abruptly decrease at deeper levels and rarely exceed a depth of 10 km (Cameli et al., 1993; 1998). Measurements of bottom hole temperatures suggest values ranging between 400°C and 450°C (Fig. 8) at the depth of the K-horizon.

On the basis of these characteristics, the lozenge-shaped band and the K-horizon are interpreted as a kinematically active mid-crustal level along the present rheological boundary, between the brittle upper part of the crust and the ductile lower part (Cameli et al., 1993; 1998). The K-horizon can therefore be explained as a seismic marker indicating the top of the crustal shearing plane (Fig. 9). The K-horizon was recently recognised throughout Southern Tus-

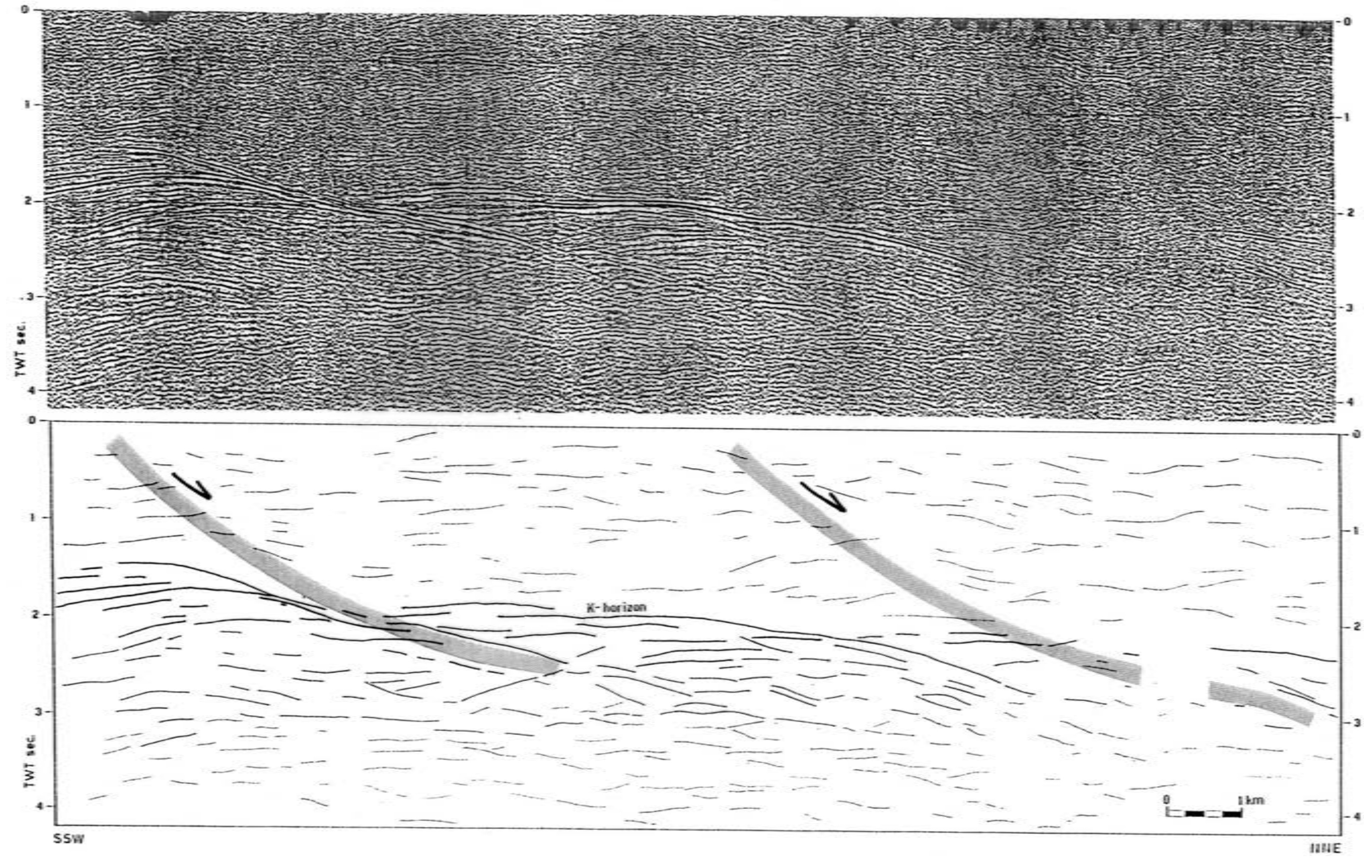

Fig. 6 - Unmigrated SSE-NNE seismic profile (top) and its line drawing (bottom) across the Larderello geothermal field. The K-horizon is affected by normal faults which are related to the third extensional event. The normal faults tend to flatten in the lozenge-shaped band (after Cameli et al., 1993, modified).

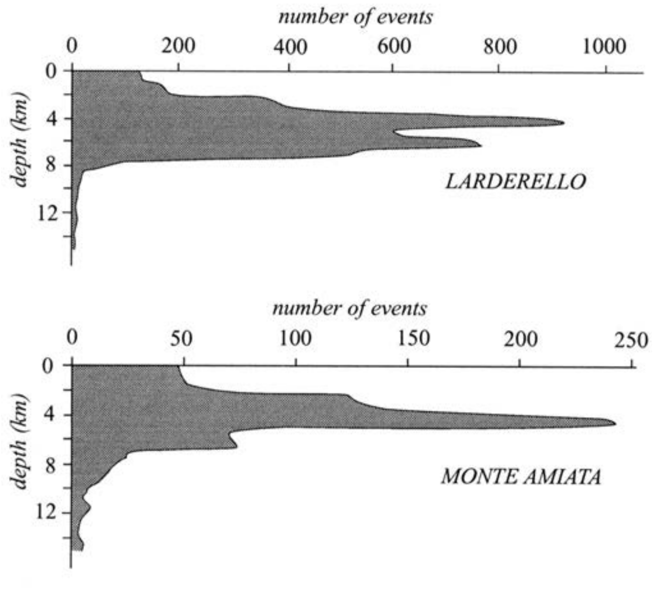

Fig. 7 - Distribution with depth of the hypocenters of local seismic events recorded by the seismic network of the Larderello (26 stations) and Monte Amiata (12 stations) geothermal fields. Larderello geothermal field: 3745 events (Magnitude ≥ 0.5) occurring in the period 1977-1995 were considered. Monte Amiata geothermal field: 839 events (Magnitude ≥ 0.5) occurring in the period 1978-1992 were considered (after Cameli et al., 1998).

cany by the new crustal reflection seismic lines CROP 3 and CROP 18 (Decandia et al., 1998; Cameli et al., 1998). From this information, a map of the K-horizon, i.e. of the top of the ductile part of the continental crust, in Southern Tuscany was recently drawn (Fig. 10). The K-horizon turns out to be shallower where the heat flow is higher, suggesting a close relationship between heat flow and K-horizon depth (Baldi et al., 1994a; Cameli et al., 1998).

Information about deeper crustal levels comes from the CROP 03 crustal reflection seismic line. This line shows that the crust of Tuscany is divided into a poorly reflective upper part and a highly reflective lower part, limited at the top by the K-horizon (Cameli et al., 1998; Decandia et al, 1998; Marson et al., 1998). The ductile part of the crust, below the K-horizon, is characterized by bright reflections which could be produced by the presence of pressured fluids (Batini et al., 1985) in ductile shear zones. These fluids would also favour the shearing necessary to accomodate extension (Decandia et al. 1998). The reflections end at about 7 s TWT, i.e. at a depth of 22 km (Decandia et al. 1998). Stretching occurs along crustal extensional shear zones dipping eastwards; these shear zones have been migrating eastward through time (Decandia et al., 1998).

From seismic reflection studies (Decandia et al., 1998) and studies on seismic waves (Calcagnile and Panza, 1980), the roof of the asthenosphere is estimated to a depth of about 30 km. The proximity of the asthenosphere explains the high heat flow which characterizes the Southern Tuscany.

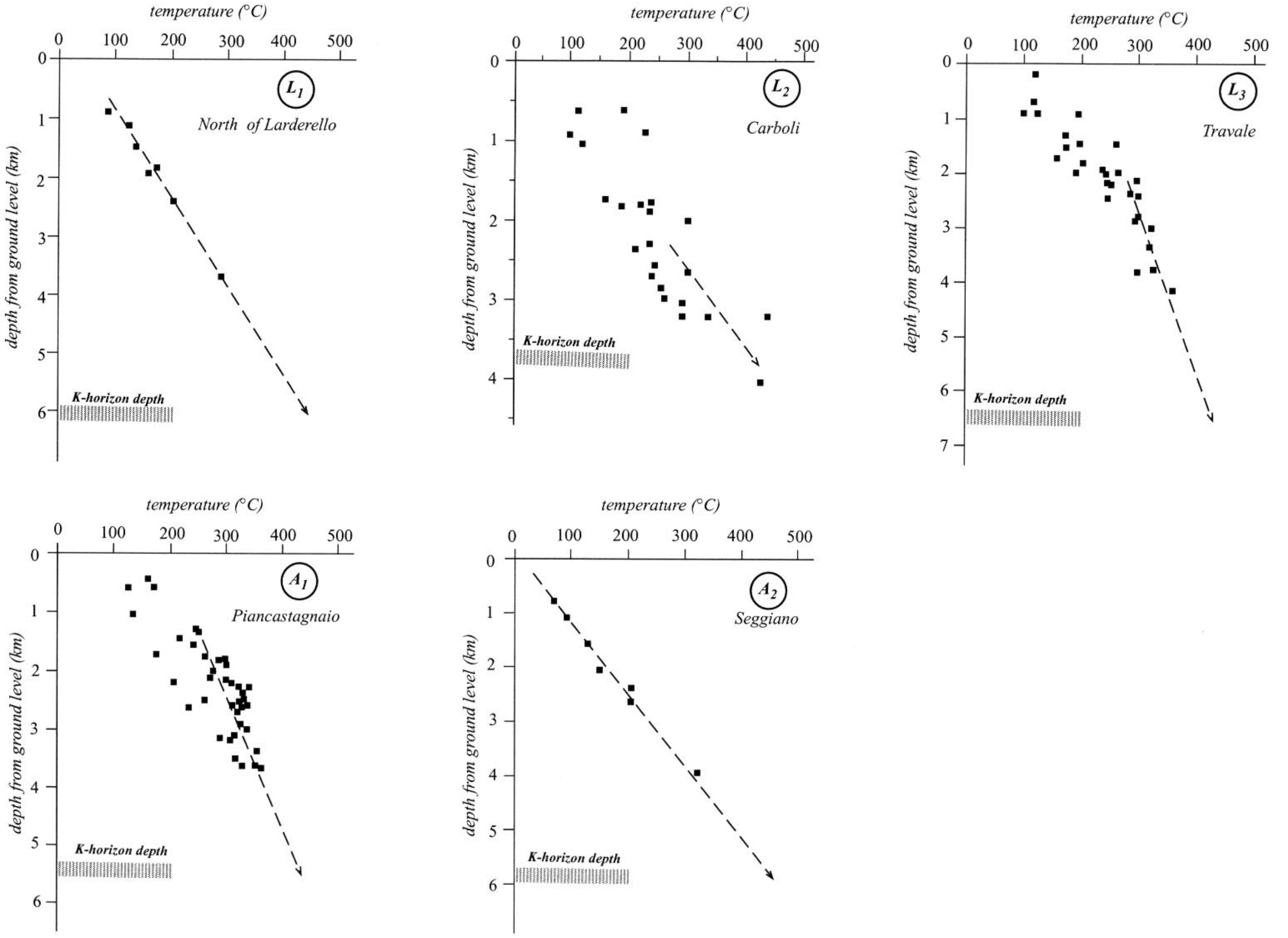

Fig. 8 - Temperatures measured in the geothermal wells of Larderello (L_1, L_2 and L_3) and Monte Amiata (A_1 and A_2) fields. The arrow indicates the extrapolated temperature, at the depth of the K-horizon where the temperature is always ranging between 400°C and 450°C (after Cameli et al., 1998).

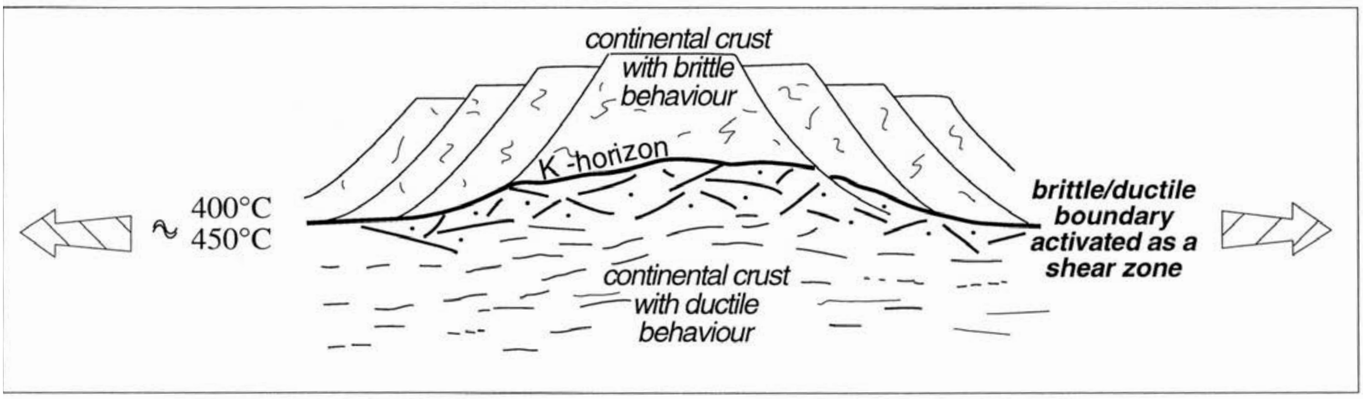

Fig. 9 - Structural interpretation of reflectivity, hypocentral distribution and temperature in the Larderello and Monte Amiata geothermal fields. (after Cameli et al., 1993).

MAGMATISM

In eastern Corsica and Southern Tuscany, Tertiary magmatism ranges in age between Middle Miocene and Quaternary, becoming younger eastwards (Fig. 1). Tuscan and Corsican magmatism was produced by a process in which crustal and basic sub-crustal magmas have mixed (Innocenti et al., 1992). However, magmas with greater crustal affinity are distinguished from those with greater mantle affinity (Serri et al., 1993, with ref.).

Magmatism is coeval with extensional tectonics. Because both mantle and crust are affected by partial melting, it can be inferred that the entire lithosphere is affected by extension, at least since Langhian (age of the Sisco lamproites; Serri et al., 1993).

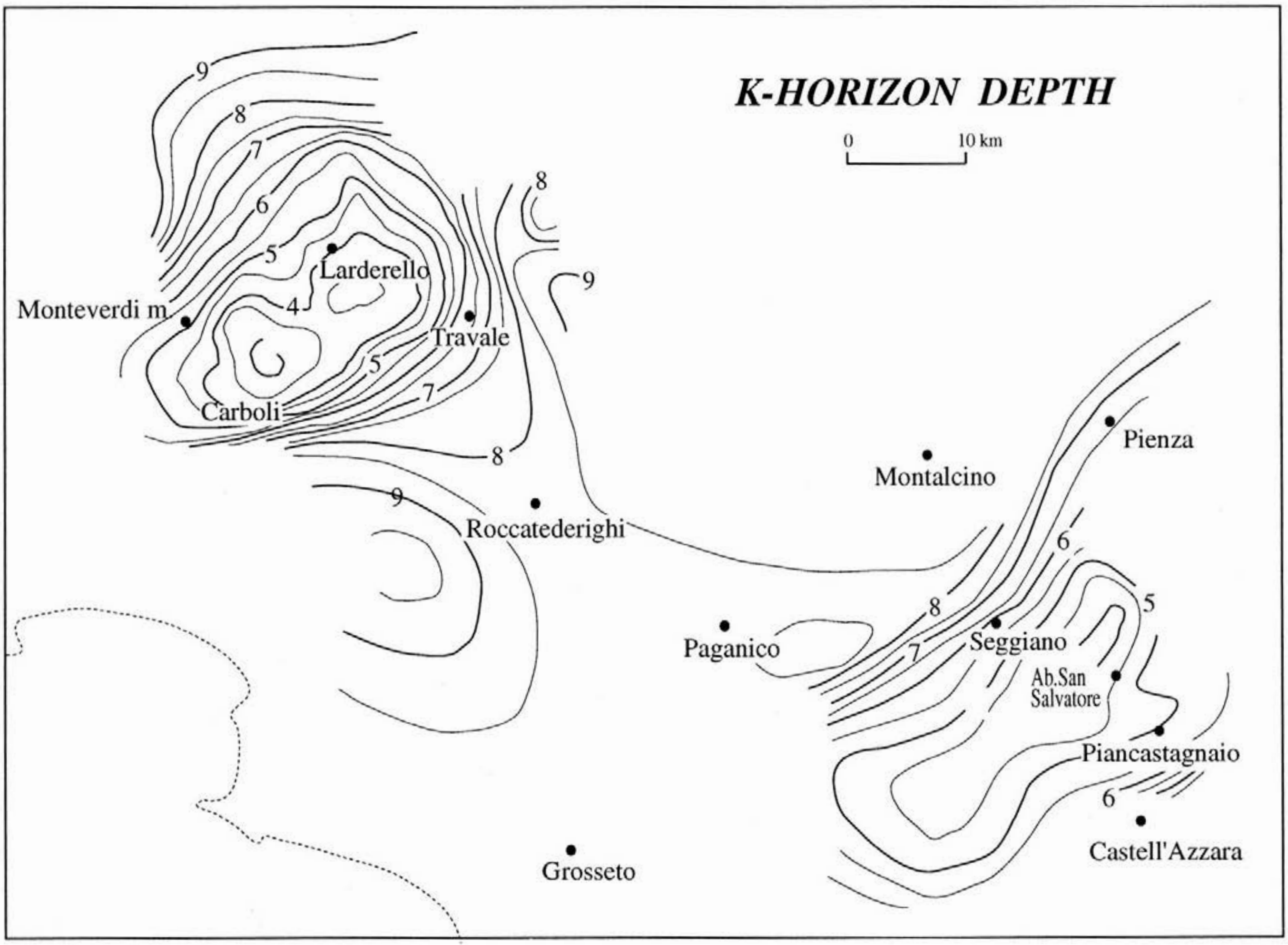

Fig. 10 - Contour lines in kilometers (interval: 0.5 km) of the depth of the K-horizon based on seismic reflection lines acquired in Southern Tuscany (after Cameli et al., 1998).

COOLING AGES AND UPLIFT

Fig. 11 shows the cooling ages of Southern Tuscany, obtained by $^{40}Ar/^{39}Ar$ determinations in the geothermal wells of the Larderello area. Two groups of cooling ages are recorded: ≈7 Ma, corresponding to the late Tortonian, and ≈3.8-1.6 Ma corresponding to Early-Late Pliocene. The youngest cooling ages have been obtained at deeper structural levels. These ages indicate that the thermal system has been active since the late Tortonian, at least. The cooling history of the Larderello area may have been controlled by two different geological processes: either local crustal elements may cool at a constant depth or the thermal system is regional and remained stable while the crust uplifted. As already described, since the Tortonian the entire Tuscan lithosphere was affected by partial melting. Therefore, the thermal system was presumably regional and remained regionally stable. These considerations suggest that cooling ages were related to crustal uplift rather than thermal decay (Dallmeyer et al., 1995). Crustal uplift events are also indicated by regional unconformities recognized in the Miocene and Pliocene sequences (Bossio et al., 1993, with ref.). Fig. 12 shows the correlation of Miocene and Pliocene subsidence and uplift events with coeval magmatic activity in Southern Tuscany. The periods of magmatic activity (i.e. heating of the lithosphere), correspond to erosional events and/or a decrease in the water column.

Recent uplift is indicated by the altitude of Middle Pliocene coastal sediments (Fig. 13). Post-Middle Pliocene uplift rates range from 0.03 mm per year to 0.23 mm per year, for western and eastern Tuscany, respectively. This rapid uplift is explained by the high heat flow which characterizes Southern Tuscany.

Uplift of Southern Tuscany contrasts with the thermal subsidence which edominated in the northern Tyrrhenian

$^{40}Ar/^{39}Ar$ COOLING AGES

WELL	DEPTH (m)	ROCK	MINERAL	AGE	REF.
S. Pompeo	1899	phyllite	whole rock	7.3 ± 0.1	3
	2718	micaschist	muscovite	2.53 ± 0.07	3
	2963	micaschist	biotite	1.61 ± 0.12	2
Selvaccia	3100	gneiss	muscovite	7.52 ± 0.04	3
	3506	gneiss	biotite	3.68 ± 0.05	3
Lumiera	2237	gneiss	muscovite	3.33 ± 0.04	3
VC 11	2946	micaschist	biotite	2.89± 0.5	3
Sasso 22	4028	gneiss	biotite	2.88 ± 0.05	2
MV7	3483	granite	biotite	3.8 ± 0.1	1

Fig. 11 - $^{40}Ar/^{39}Ar$ cooling ages from borehole samples of the Larderello area. References: 1- Villa et al. (1987); 2- Villa and Puxeddu (1984); 3- Dallmeyer et al., (1995).

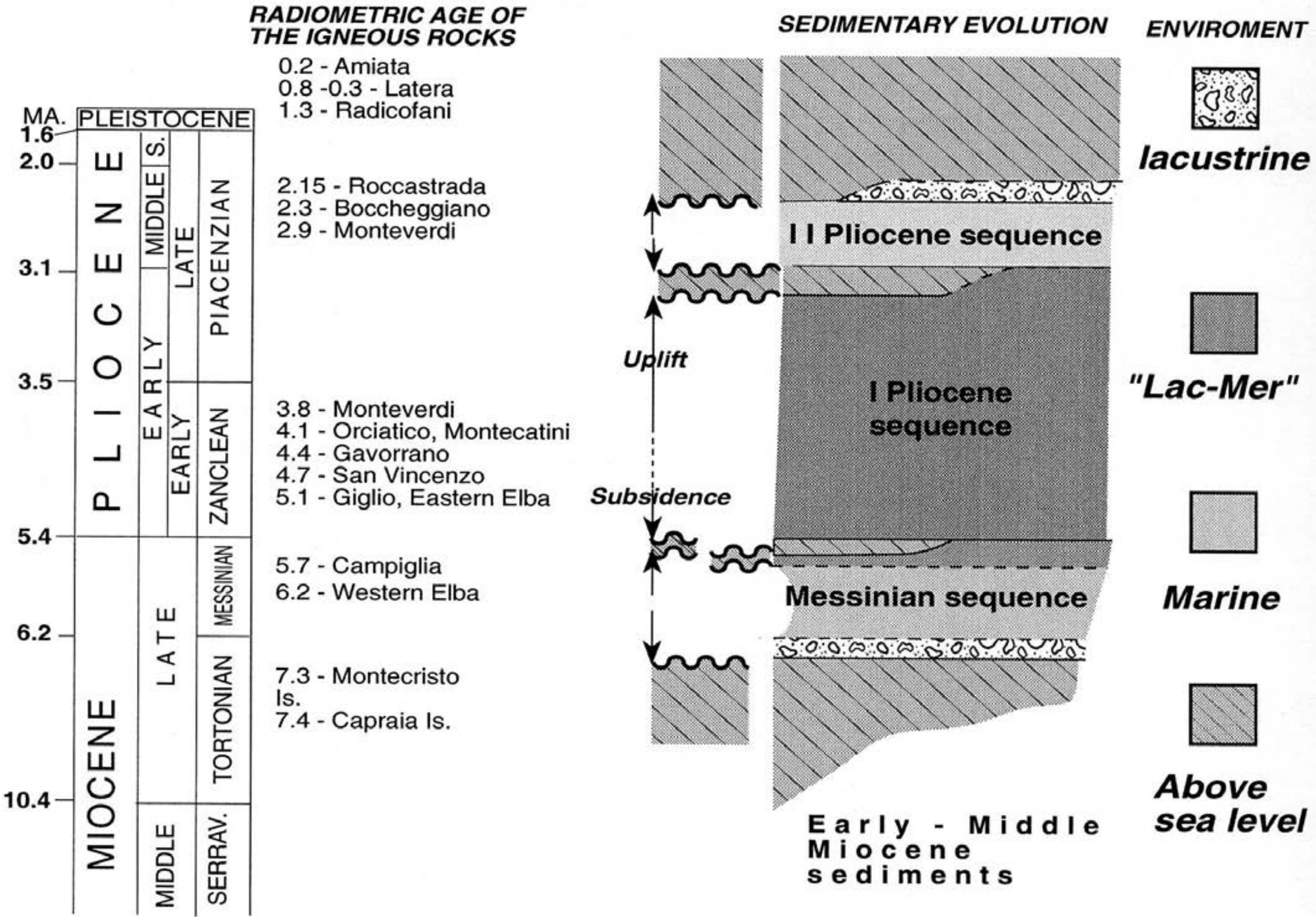

Fig. 12 - Late Miocene and Pliocene magmatic activity in Tuscany compared with the coeval sedimentary evolution (From Baldi et al., 1994b). Radiometric ages are from Ferrara and Tonarini (1985) and Serri et al. (1993).

Basin since the Middle Pliocene, as demonstrated by several studies of seismic lines (Zitellini et al., 1986; Bartole, 1990; Bartole et al., 1991; Bartole, 1995).

DISCUSSION

We will focus on two main points: (a) the development of extensional structures and (b) the geodynamic context in which extension took place.

(a) Regarding the first point, three main detachment horizons are recognizable in Tuscany. One was active during the Middle Miocene and runs within the Upper Triassic evaporites which mark the initial location of the brittle/ductile boundary. The second occurs along the Paleozoic phyllites and was active during Serravallian-late Messinian. The third one corresponds to the shear zone topped by the K-horizon. This shear zone is located at the present brittle/ductile boundary. Because the normal faults of the second extensional event tend to flatten in the Paleozoic phyllite and because this detachment level is located between the oldest and the present brittle/ductile boundary, we suggest that the Paleozoic phyllites also marked the brittle/ductile boundary during the Serravallian-late Messinian. This hypothesis suggests migration of the brittle/ductile boundary to deeper levels due to the progressive exhumation and uplift events which accompanied the Neogene extensional tectonics. The relatively shallow depth of the present brittle/ductile boundary is a result of the high heat flow which characterizes Tuscany. Because partial melting of the Tuscan lithosphere is documented since the Late Miocene, it may have been controlled by heat flow during the second extensional event.

(b) Regarding the geodynamic context in which extensional tectonics took place, different hypotheses have been proposed:

i- Extension of the inner zone and compression of the outer zone resulted from subduction and westward dipping of the sinking slab of the Adriatic continental lithosphere under the Northern Apennines, and from the eastward migration of the back-arc/chain/foredeep system (Boccaletti and Guazzone, 1972; Scandone, 1979; Royden et al., 1987; Serri et al., 1993; Keller et al., 1994). The sinking slab and its eastward migration could have caused the extra load necessary to flex the Adriatic crust and to create the space for a new eastern foredeep, at surface level (Royden et al., 1987; Royden, 1988; Doglioni, 1991; Serri et al., 1993; Keller et al., 1994). In this context, deep crustal rocks are exhumed initially during crustal thickening and, later, during back-arc crustal extension (Jolivet et al., 1994).

ii- The Northern Apennines are subjected to post-collisional extensional tectonics. The coexistence of inner extensional and outer compressional structures is the result of gravitational processes related to the uplift of the inner Northern Apennines; the vertical movements

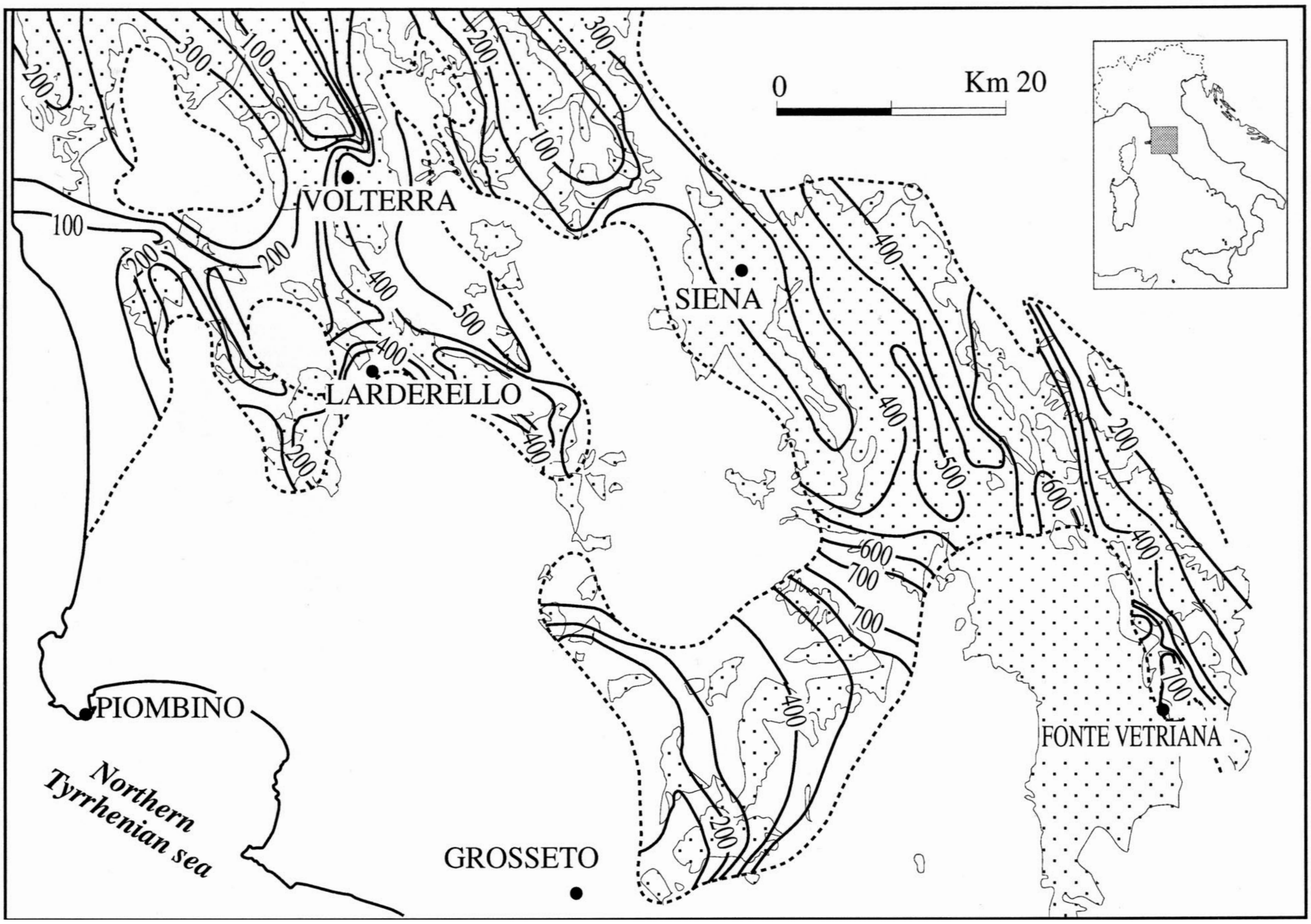

Fig. 13 - Present altitude of Middle Pliocene coastal sediments. Contour lines are in meters (100 m interval). Dotted areas indicate the outcrops of Pliocene sediments. Dashed lines outline areas where no stratigraphic data are available (after Bossio et al., 1995).

are explained in several ways: a- as a result of an uprising mantle diapir (Wezel, 1982; Locardi 1982; Locardi and Nicolich, 1992); b- as an isostatic process which developed after crustal thickening (Carmignani and Kligfield, 1990); c- as asymmetrical post-collisional shear, dipping eastward, which caused uprising of the asthenosphere and anomalous heat flow under Tuscany (Decandia et al., 1998). Rifting itself produced the horizontal forces which developed new foredeeps (Lavecchia et al., 1996; Decandia et al., 1998). Marson et al. (1998), used gravity data to demonstrate that the crustal flexure of the outer zone could derive from a horizontal push of 6.2×10^{11} N/m. This value is similar to that necessary to stretch the continental crust (Lynch and Morgan, 1987, with ref.). Decandia et al. (1998) proposed to correlate this force with the rifting process affecting the inner zone of the Northern Apennines; by action of this pushing force, the crust of the outer zone is broken and bent because there is no lateral escape, as continental crust occupies the easternmost regions (Fig. 14).

Some authors (Boccaletti et al., 1992; Boccaletti et al., 1995; Boccaletti et al., 1997) suggest that extension has been the prevalent tectonic process since Early Pliocene only. This hypothesis cannot explain the present relationship between the Ligurid Units and the Upper Triassic anhydrites and the lenticular shape of the Verrucano Group: these are undoubtedly pre-Early Pliocene crustal thinning features.

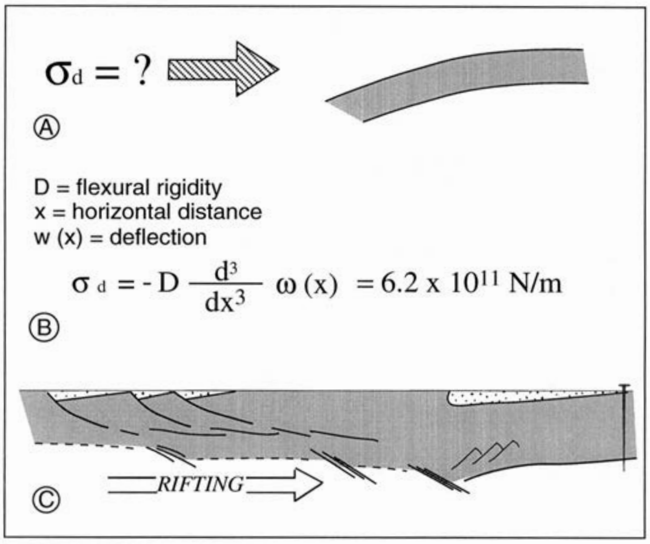

Fig. 14 - A. The crust of the outer zone is assumed to be a continuous elastic plate, deflected by a distributed load, B. which is proportional to the derivative of the curvature. The result is similar to the force necessary to stretch the lithosphere (1-5 $\times 10^{12}$ N/m, Lynch and Morgan 1987, with ref.). In accord with this result, the geological interpretation, C. explains the horizontal force which bends the crust of the outer zone as a result of the rifting process. The crust of the outer zone is broken and deflected because lateral escape is prevented (pin) by the easternmost continental crust (after Decandia et al., 1998; modified).

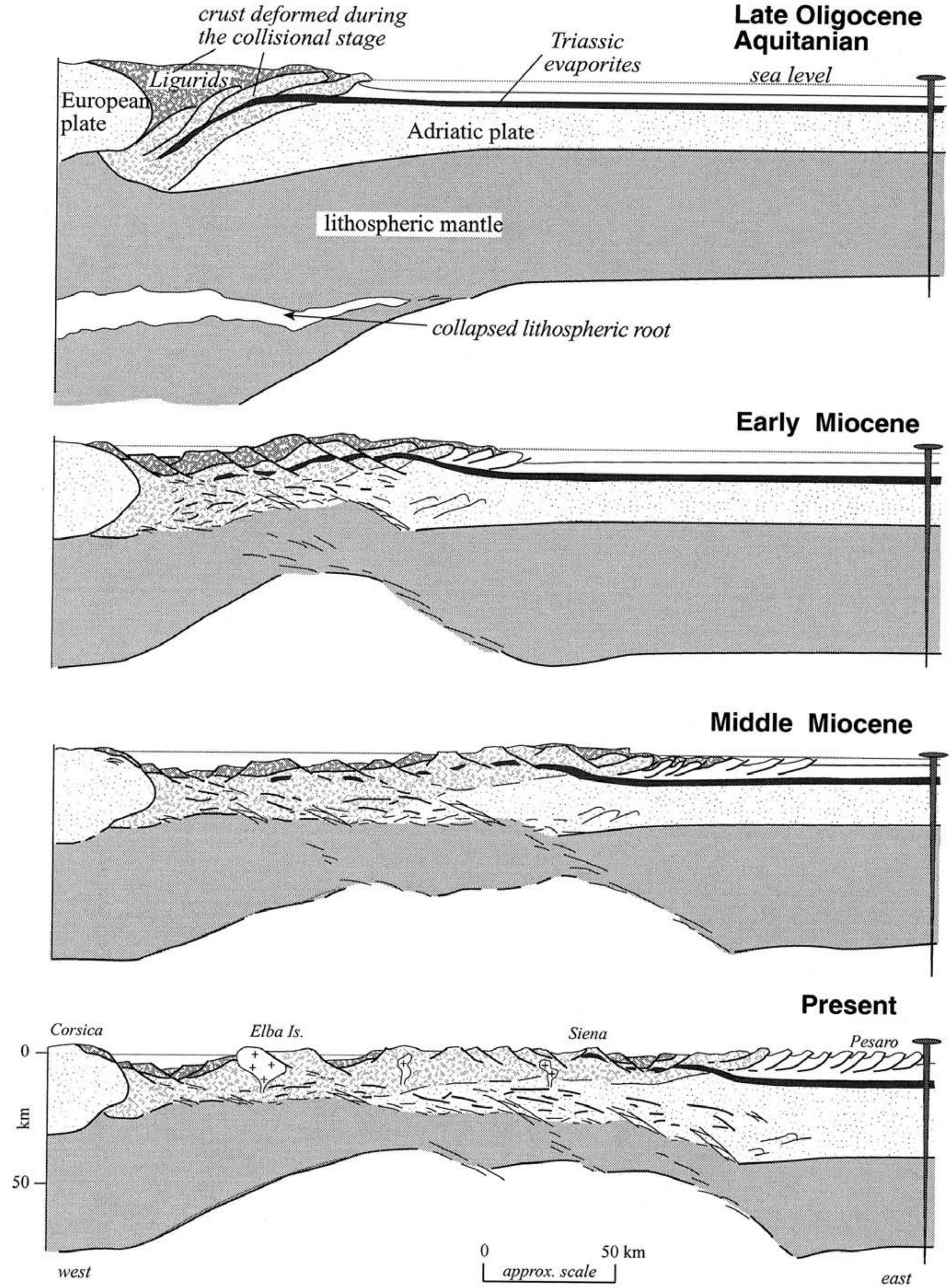

Fig. 15 - Idealized post-collisional evolution of the Northern Apennines. Deformation is driven by asymmetrical shear zones, that migrate eastwards. Uplift events caused eastward thrusting of the Ligurian Units and the formation of the thrust belt of the outer zone. According to this hypothesis, the forces necessary to bend the crust of the outer zones are produced by the rifting process itself. Below the cover, deformation is caused by horizontal rifting forces (after Decandia et al., 1998; modified).

CONCLUSIONS

Exhumation of deep crustal rocks, thinning of the crust, and anomalous heat flow are features which allow to consider Southern Tuscany as an ideal region for studying the post-collisonal evolution of the Northern Apennines. In addition, the recent uplift of this thinned crustal province allows to investigate structures which are usually located hundreds of meters below sea level, as in the northern Tyrrhenian Basin. Combining data from fieldwork and stratigraphic studies with borehole data and seismic reflection lines, we propose a possible post-collisional evolution of the Northern Apennines (Fig. 15).

Collapse of the lithospheric roots at the end of the collisional stage is hypothesized. The rifting process is controlled by eastward dipping asymmetrical shears, and therefore the thinning of the lithospheric mantle is offset with respect to crustal thinning. Uplift events, which presumably developed where the lithospheric mantle was thinned, caused eastward thrusting of the Ligurian Units and development of a fold thrust belt in the cover of the outer zones. According to this hypothesis, the forces necessary to bend the crust of the outer zone would be produced by rifting itself.

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