Understanding the crustal structures of southern Tuscany: The contribution of the CROP18 Project

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ABSTRACT The CROP 18 Project (1995-2002) has dealt with the relationships between crustal structures and geothermal resources in southern Tuscany. The acquisition of a 120 km-long deep seismic reflection survey is also included in this Project. Here we discuss the compressional and extensional regimes, both proposed as explanation for the Neogene-Quaternary structures of southern Tuscany. We also discuss the close relationship of seismic reflectivity, CROP 18-lines orientation and Pliocene-Present tectonic structures. The main results are: (a) the extensional framework, which has been active since the Early-Middle Miocene, explains the structural features and tectonic evolution of southern Tuscany better than compression; (b) the upper crust of southern Tuscany is characterised by widespread boudinage; (c) the mid-lower crust is largely affected by magmatic intrusions; (d) NE-dipping extensional shear zones are imaged in the upper and lower crust; these are connected through a mid-crustal shear zone, located at the brittle/ductile transition. These shear zones could act as preferential pathways for upward migration of metamorphic and magmatic fluids and mantle elements, now characterising the geothermal fluids of the Larderello area.

1. Introduction

Continental, extensional tectonic environments with high heat flow indicate the presence of geothermal systems, independently from the geodynamic context in which they are located (*e.g.* Muffler and Duffield, 1995; Barbier, 2002). The CROP 18 Project, which includes the acquisition of deep seismic lines through the most important geothermal areas of Tuscany (Fig. 1), aims at investigating the relationships between geothermal resources and crustal structures. Southern Tuscany is characterised by a thin crust [of about 22-24 km: Giese *et al.*, (1981), Nicolich, (1989), Ponziani *et al.*, (1995)], a thin lithospheric mantle [of about 40 km: Calcagnile and Panza, (1981), Suhadolc and Panza, (1989)] and high heat flow with local peaks of up to 1000 mW/m^2 and 600 mW/m^2, corresponding to the Larderello and Mount Amiata geothermal areas, respectively (Mongelli *et al.*, 1989; Della Vedova *et al.*, 2001; Bellani *et al.*, 2004). These features, also highlighted by the CROP 03 Project (Pialli *et al.*, 1998) and CROP03 deep seismic reflection profile (Barchi *et al.*, 1998; Decandia *et al.*, 1998; Lavecchia *et al.*, 2004), underline the relationship between a thin lithosphere and the occurrence of geothermal resources. Consequently, a crustal project entirely dedicated to southern Tuscany and its geological features, named CROP 18 Project, was proposed (Lazzarotto and Liotta, 1994). Furthermore, during the time-period in which the CROP 18 Project was carried out, new studies in the field (Bonini *et al.*, 1994, 2001; Boccaletti *et al.*, 1999) as well as deep (Finetti *et al.*, 2001; Bonini and Sani, 2002) geological structures explained the tectonic evolution of Tuscany in the framework of a compressional setting, which was active from the Cretaceous to the Pliocene and/or Pleistocene. This view challenged the Miocene-Present extensional context invoked to explain the southern Tuscan structures [Trevisan, (1952), Boccaletti *et al.*, (1971), Locardi and Nicolich (1982), Lavecchia (1988), Carmignani and Kligfield, (1990), Jolivet *et al.*, (1994), among many others]. In this debate, the CROP 18 Project represented a significant contribution for an ample revision of and to increase the knowledge on the tectonic evolution of southern Tuscany (Brogi *et al.*, 2005b). Here we present the main results of the CROP 18 Project: we report the state of the art on the compression vs. extension interpretation and show a geological interpretation of the CROP 18 seismic reflection survey. Finally we propose a possible link between the continental structures and the geothermal resources in southern Tuscany.

2. Geological framenwork

The Northern Apennines originated from the collision (Cretaceous-Early Miocene) between the Adria microplate and the European plate, represented by the Sardinia-Corsica Massif. This process determined the stacking of several tectonic units (Fig. 2) which are, from the top: (1) The Ligurian Units, which include the Ligurian and the Subligurian Complexes. These are respectively composed of: remnants of Jurassic oceanic crust and its related Jurassic-Cretaceous sedimentary cover; (2) Cretaceous-Oligocene flysches. These complexes were thrust eastwards over the Tuscan Nappe during Late Oligocene-Early Miocene times; (3) The Tuscan Nappe derives from the internal Tuscan domain and includes sedimentary rocks ranging from Late Triassic evaporites to Jurassic carbonate platform, Cretaceous-Oligocene pelagic sediments and Late Oligocene-Early Miocene turbidites. During the Late Oligocene-Early Miocene, the Tuscan Nappe, with the Ligurian Units at the top, detached themselves from the Late Triassic evaporite level and thrust themselves over the external Tuscan domain, giving rise to the metamorphic Tuscan Nappe (external zone).

In Tuscany, the substratum of the Ligurian Units and Tuscan Nappe is known through fieldwork and the drilling of deep wells in the Middle Tuscan Range and in the Larderello and Mount Amiata geothermal fields (Fig. 1). The substratum is composed of two units (Fig. 3): the upper unit is referred to as the Monticiano-Roccastrada Unit, made up of the Metamorphic Late Triassic-Eocene Tuscan Nappe (Montagnola Senese area, Fig. 1), Triassic quartz metaconglomerates, quartzites and phyllites (Verrucano Group *Auct.*), Palaeozoic phyllites and micaschists, and the lower one corresponds to the Gneiss Complex.

After the emplacement of the tectonic units, extension affected the inner Northern Apennines (*i.e.* northern Tyrrhenian Basin and southern Tuscany) from the Early-Middle Miocene period (Jolivet *et al.,* 1990; Carmignani and Kligfield, 1990; Carmignani *et al.*, 1994*,* 1995; Rossetti *et al.*, 1999; Brunet *et al.,* 2000). Extension is coeval with magmatism from Late Miocene, deriving from mixing of crustal and mantle sources (Serri *et al.*, 1993). Boreholes in the Larderello area encountered felsic dykes and granitoids ranging between 3.8 and 1.0 Ma in age (Dini *et al.*, 2005). This extensional framework is thoroughly argued by Finetti *et al.* (2001) and Bonini and Sani (2002 and references therein). Their point of view will be discussed later on. Since the

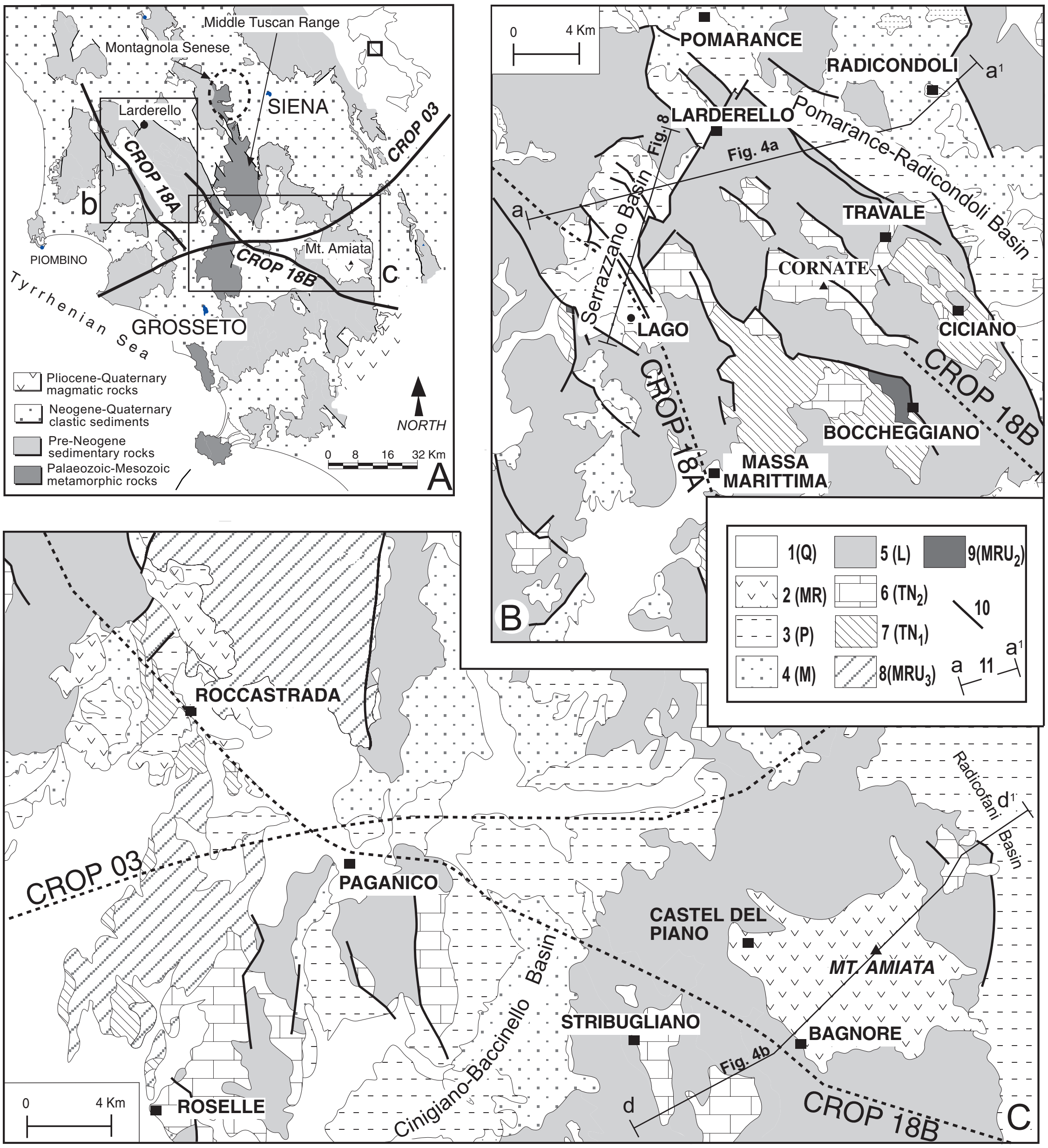

Fig. 1 - Geological sketch maps of (A) southern Tuscany, (B) Larderello and (C) Mt. Amiata geothermal areas. The traces of the CROP 18 and 03 lines are shown. Symbols: (1) Q: Quaternary continental sediments; (2) MR: Pliocene-Quaternary magmatic rocks; (3) P: Pliocene marine sediments; (4) M: Middle-Late Miocene continental, brackish and marine sediments; (5) L: Ligurian Units (Jurassic - Oligocene); Tuscan Nappe: (6) TN_2: Late Triassic-Early Miocene sedimentary sequence; (7) TN_1: Late Triassic evaporites; (8) MRU_3: quartz metaconglomerates, quartzites and phyllites (Triassic Verrucano Group); (9) MRU_2: Palaeozoic Phyllites; (10) normal faults; (11) traces of the geological sections given in Figs. 4 and 6.

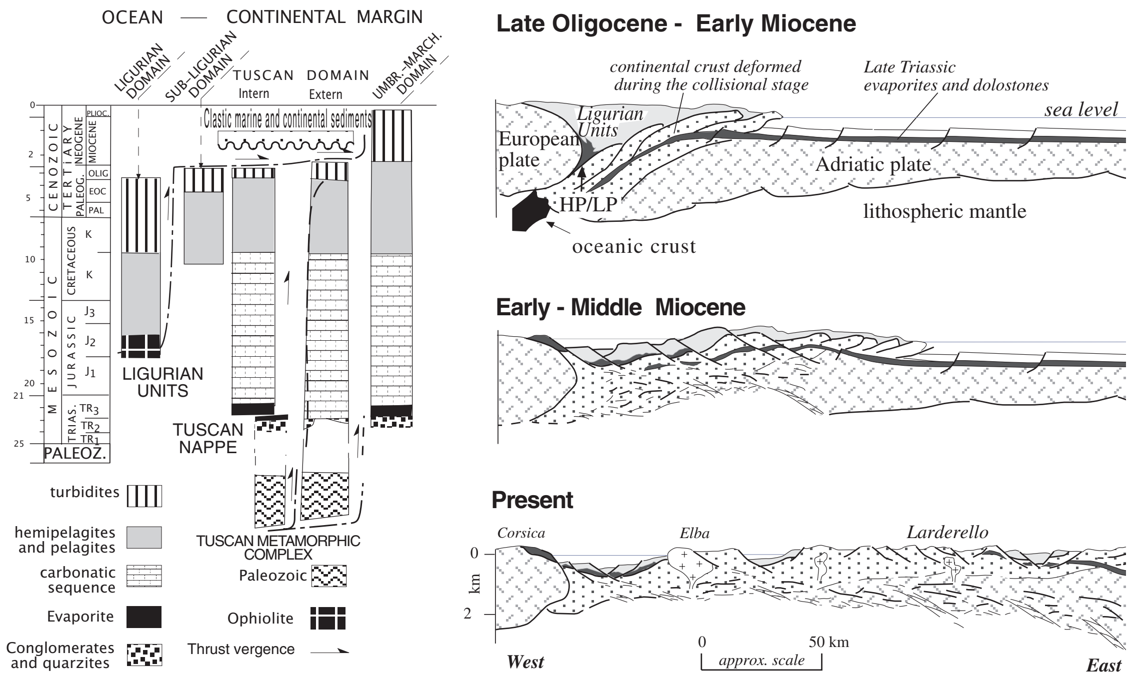

Fig. 2 - Left: relations among the different tectonic units of Northern Apennines and related palaeogeographical domains. Right: schematic crustal geological cross-sections showing the collisional and post-collisional evolution through the Northern Apennines [after Carmignani *et al.*, (1994) and Liotta *et al.*, (1998), modified; Brogi *et al.*,(2005c)].

Middle Pliocene, southern Tuscany has been affected by rapid surface uplift (Bartolini *et al.*, 1983; Dallmeyer and Liotta, 1998).

3. Geological features in the upper crust

The present-day upper crust (*i.e.,* the crust characterised by dominant frictional deformation) is made up of: a) metamorphic and sedimentary rocks deriving from the inner Northern Apennines palaeogeographic domains; b) Middle-Late Miocene and Early-Middle Pliocene post-collisional sediments; c) magmatic rocks, emplaced from the Late Miocene to 1 Ma ago. We present the main structures affecting the upper crust considering that compression developed in the Cretaceous-Early Miocene time span, while extension, in the Miocene - Present time range.

The compressional structures are related to the stacking of the tectonic units belonging to the Northern Apennine palaeogeographic domains. In the tectonic units from the Tuscan domain, Late Oligocene-Early Miocene embricated thrusts affected both the already folded metamorphic rocks (Costantini *et al.*, 1988; Elter and Pandeli, 1990; Bertini *et al.*, 1991; Giorgetti *et al.*, 1998; Liotta, 2002) and sedimentary successions (Brogi, 2004; Brogi *et al.*, 2005a, 2005b).

All the previous structures that developed were deformed by extensional tectonics which affected the inner Northern Apennines since Early-Middle Miocene (Jolivet *et al.*, 1990; Carmignani and Kligfield, 1990; Carmignani *et al.*, 1994, 1995; Rossetti *et al.*, 1999; Brunet *et*

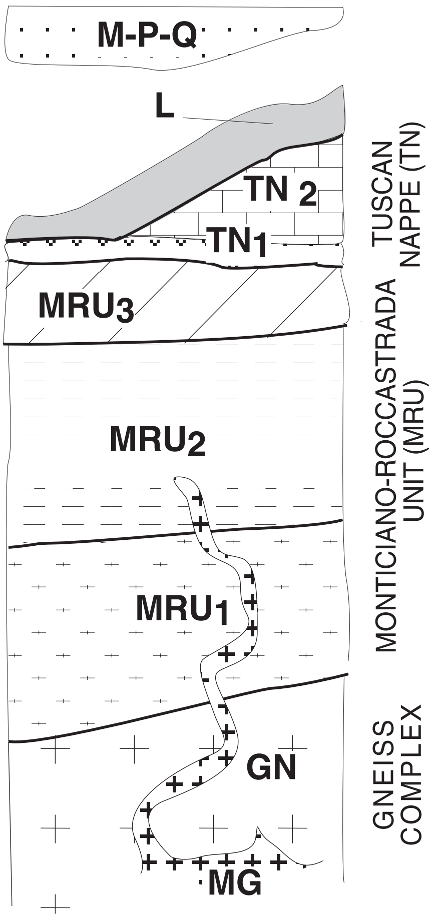

Fig. 3 - Tectono-stratigraphic units reconstructed in the Larderello area and considered representative for the whole of southern Tuscany: M-P-Q, Middle-Late Miocene, Early-Middle Pliocene and Quaternary sediments; L, Ligurian Units; Tuscan Nappe (TN): TN_2, Early Miocene-Rhaetian sequence; TN_1, Late Triassic evaporites; Monticiano-Roccastrada Unit (MRU): MRU_3, Mesozoic - Palaeozoic Group, made up of: Late Triassic-Eocene Metamorphic Tuscan Nappe, Triassic Verrucano Group, and Palaeozoic phyllites and limestones; MRU_2, Palaeozoic Phyllites; MRU_1, Palaeozoic Micaschists; GN, Gneiss Complex; MG, Pliocene-Quaternary magmatic intrusions [after Bertini *et al.*, (1991), modified].

al., 2000). Although extension is a continuous process through time, three different events were recognised, in the Larderello area (Baldi *et al.*, 1994; Dallmeyer and Liotta, 1998). The first and second extensional events determined the thinning of the Ligurian Units, the boudinage of the Tuscan Nappe and of the Verrucano Group. In the gap between boudins, the Ligurian Units, the highest units in the orogenic tectonic pile, overlie the Late Triassic evaporites, structurally sited at the base of the Tuscan Nappe and/or the Palaeozoic phyllites, positioned at the base of the Verrucano Group (Fig. 4).

In the Late Miocene, continental to marine sediments deposited in the tectonic depressions deriving from the boudinage process. The Late Miocene structures and sediments were later dissected by the Pliocene-Present normal faults of the third extensional event (Fig. 4). In the Larderello area, three Pliocene-Present different systems of NE-dipping normal faults, soling out at the present brittle/ductile transition, have been recognised (Brogi *et al.*, 2003). Their damage zones are interpreted as the main structural pathways (Bellani *et al.*, 2004) for the flow of hot geothermal fluids consisting of meteoric water with minor contribution of magmatic and metamorphic fluids and isotopic elements from the mantle (D'Amore and Bolognesi, 1994; Minissale *et al.*, 2000; Magro *et al.*, 2003).

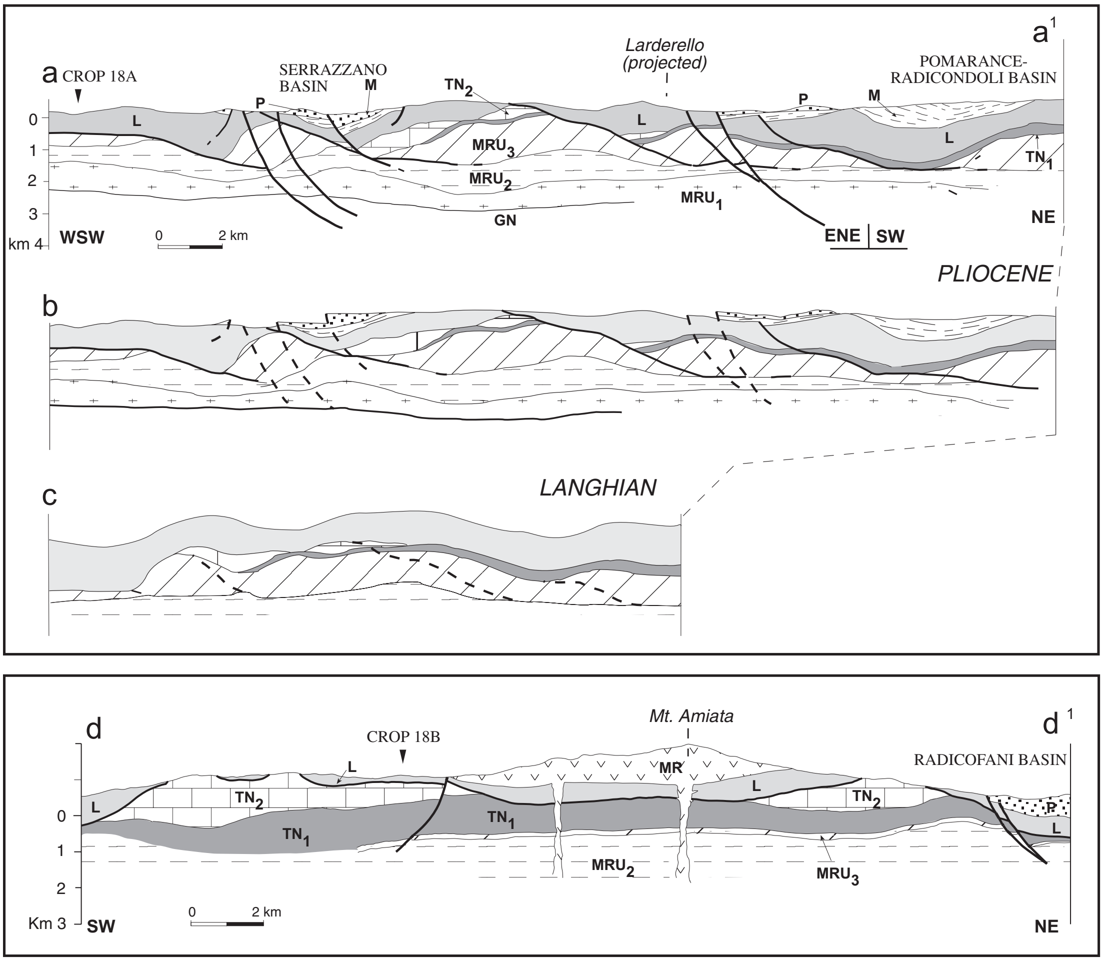

Fig. 4 - Geological cross-section through the Larderello (top) and Mt. Amiata (bottom) geothermal areas constructed from borehole data, interpretation of seismic reflection lines and field mapping. Their traces are shown in Fig. 1. (a) Present structural setting; (b) Reconstructed Pliocene geological section. Miocene sediments are preserved in the tectonic depressions linked to the boudinage of the Verrucano Group, which occured during the second extensional event; Early and Middle Pliocene sediments unconformably overlie Late Miocene sediments which were deformed during deposition. (c) Reconstructed Langhian geological section assuming no change in kinematic vectors during extensional tectonics. The restoration assumes no change in bed length in the Mesozoic-Paleozoic Group or in the carbonatic and terrigenous part of the Tuscan complex. No change in bed volume is assumed in the Ligurian units, in the Triassic evaporites or in the Phyllite-Quartzite and Micaschist Groups. Pliocene and Langhian cross-sections were based on the present sea-level as a datum plane. (d) Present structural setting through the Mount Amiata area. The volcanic outcropping rocks are dated from 300 to 190 Ka (Ferrari *et al.*, 1996). Other symbols as in Fig. 3 [after Baldi *et al.*, (1994) and Batini *et al.*, (2003)].

4. Geological features in the middle and lower crust

Information on the middle and lower crust (*i.e.* those parts of the crust typified by dominant brittle/plastic and plastic deformation, respectively) derives mainly from seismic reflection lines, acquired for the geothermal exploration (Batini *et al.*, 1978; Gianelli *et al.*, 1988; Cameli *et al.*, 1993) and for the CROP 03 Project (Pialli *et al.*, 1998).

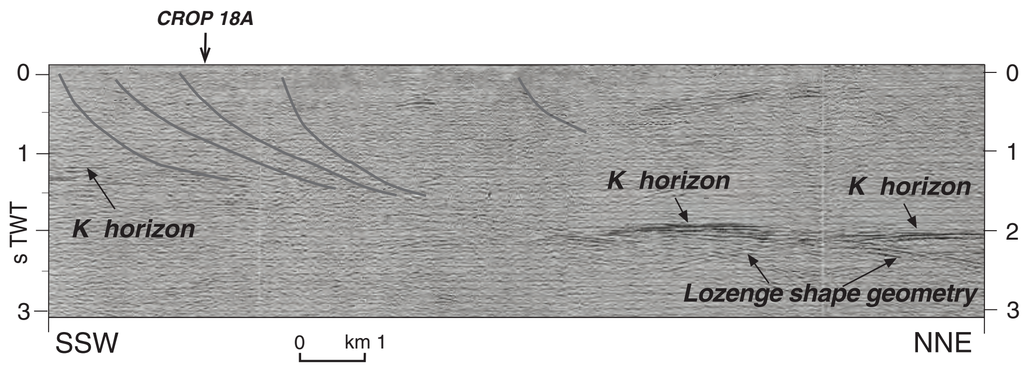

Fig. 5 - Part of a commercial unmigrated seismic reflection line through the Larderello area. See Fig. 1 for location. Datum plane is 200 m above sea-level. Normal faults, the K-horizon and the lozenge-shape geometry are highlighted [from Brogi *et al.*, (2003), modified].

The seismic reflection lines show a clear distinction between a poorly reflective upper and a highly reflective mid-lower crust (Cameli *et al.*, 1993, 1998). The top of the reflective crust is marked by a discontinuous reflector (Fig. 5) of high amplitude, referred to as the K-horizon (Batini *et al.*, 1978), which has local bright spot features (Batini *et al.*, 1985). This horizon often bounds a seismic facies characterised by reflectors with high-contrast of acoustic impedance and with a typical lozenge shape geometry (Fig. 5) both in migrated and unmigrated seismic sections (Cameli *et al.*, 1998). These seismic features, firstly recognised in the geothermal areas of Tuscany (Batini *et al.*, 1978), resulted of regional pertinence after the CROP 03 reflection seismic line acquisition (Liotta *et al.*, 1998). The K-horizon, located regionally at a depth of 8-10 km, shows a culmination in the Larderello and Mount Amiata areas where it ranges between 3 and 6 km. Pliocene-Quaternary normal faults appear to be rooted in the K-horizon (Fig. 5). At the intersection between normal faults and the K-horizon, this marker and the reflections below, lose their peculiar reflectivity (Brogi *et al.*, 2003). The depth distribution of local seismicity in the Larderello and Mount Amiata geothermal areas shows a peak at the K-horizon depth, followed by a very steep decrease with increasing depth, with almost all events having focal depth < 8 km (Cameli *et al.*, 1998; Liotta and Ranalli, 1999). The K-horizon appears to be related to a critical temperature of about 450° $\pm$ 50°C (Liotta and Ranalli, 1999). The origin of the reflectivity at the K-horizon and in the zone below has been discussed by several authors [see Gianelli *et al.*, (1997) for a review]. The occurrence of fluids can explain the observed high contrast in acoustic impedance. This, joined with temperature data, hypocentral distributions and rheological predictions (Liotta and Ranalli, 1999) led to the explanation that the K-horizon was the top of an active shear zone, located at the brittle/ductile transition (Cameli *et al.*, 1993, 1998; Liotta and Ranalli, 1999; Vanorio *et al.*, 2004).

As regards the reflectivity of the deeper levels (*i.e.* the lower crust), three different hypotheses can be considered: a) occurrence of mafic sills in the metamorphic rocks; b) occurrence of shear zones with mylonite rocks; or c) occurrence of fluids (Hamilton, 1987; Deemer and Huric, 1994; Blundell, 1990; Mooney and Meissner, 1992; Gianelli *et al.*, 1997; Liotta and Ranalli, 1999). All these phenomena can interact in an extensional tectonic setting in order to give the observed

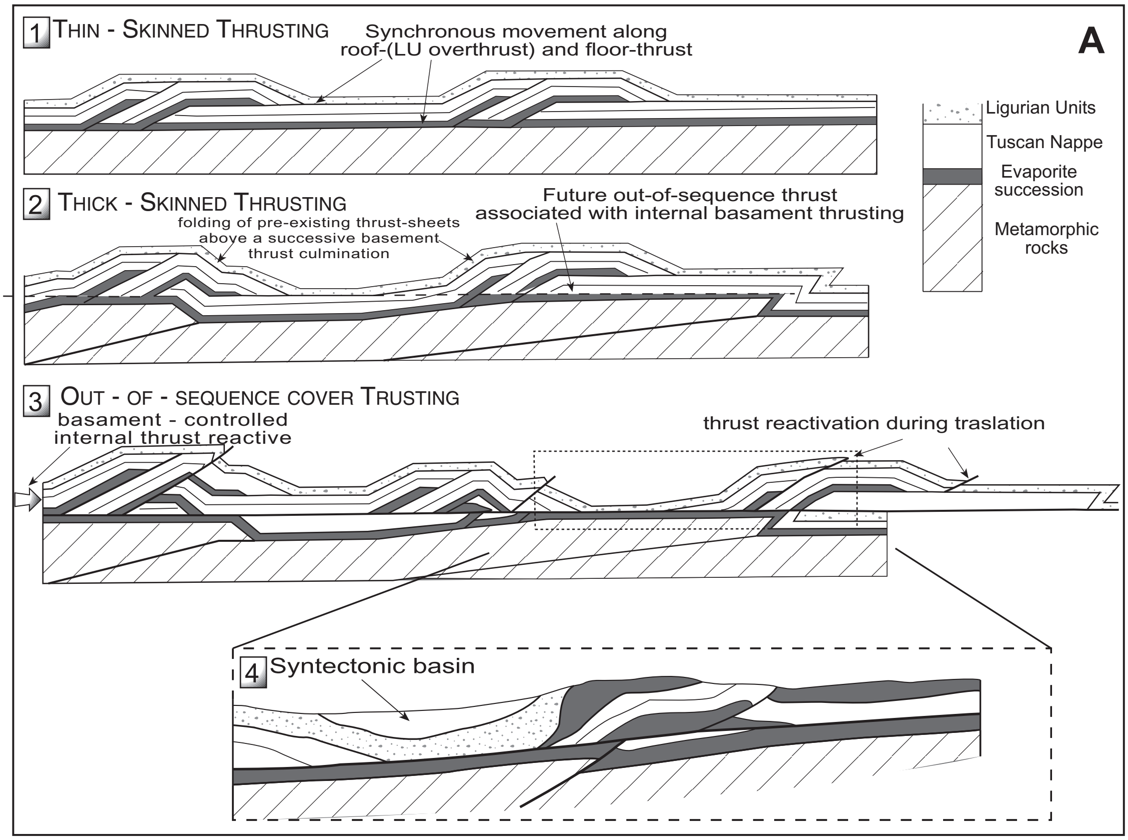

Fig. 6 - Three stages of the evolution of idealised out-of-sequence thrusts to explain limited omission of the Tuscan Nappe in southern Tuscany. Late Miocene sediments deposited in the tectonic depressions interpreted as thrust-top basins [after Finetti *et al.*, (2001), redrawn; Brogi *et al.*,(2005c)].

reflectivity. The CROP03 survey images NE-dipping extensional crustal shear zones affecting the mid-lower crust of southern Tuscany (Barchi *et al.*, 1998; Decandia *et al.*, 1998; Lavecchia *et al.*, 2004). The base of the lower crust and the crust-mantle transition is well imaged in the commercial seismic reflection lines. Generally, the base of the lower crust reflectivity is assumed to represent the Moho discontinuity (Barnes, 1994; Allmendinger *et al.*, 1987; Blundell, 1990; Mooney and Meissner, 1992). Following this interpretation, the base of the Tuscan crust appears to be located at about 24 km in the CROP 03 survey (Barchi *et al.*, 1998; Decandia *et al.*, 1998), in agreement with previous seismic refraction results (Giese *et al.,* 1981; Ponziani *et al.*, 1995).

5. Extension vs. compression regime during the Neogene-Quaternary

Neogene-Pliocene (or Neogene-Pleistocene) out-of-sequence thrusting (Fig. 6) are invoked by some authors to explain the superimposition of the Ligurian Units on the Triassic evaporites (Boccaletti and Sani, 1998; Bonini, 1999; Bonini and Sani, 2002; Finetti *et al.*, 2001). In this view, the Late Tortonian-Pliocene basins are interpreted as thrust-top basins.

Obviously, the out-of-sequence thrusting implies thickening of the crust and, consequently, the tectonic omission of the Tuscan Nappe sequence would be a minor effect. Although this evolution model makes an explanation for the widespread Pliocene-Quaternary magmatism difficult, Finetti *et al.* (2001) suggested that an originally thin lithosphere, inherited from the Triassic-Jurassic rifting, coupled with thermal erosion could explain the present Tuscan crust and lithosphere thicknesses. Bonini and Sani (2002), in addition to the reconstruction given by Finetti *et al.* (2001), do not exclude the occurrence of Messinian-Quaternary normal faults in southern Tuscany. However, these minor extensional structures are explained as an accommodation of thrust anticlines or as effects of the eastward advance and westward retreat of the northern Apennine thrust front.

Brogi *et al.* (2005c, 2005d) argued against the inheritance of an original crustal thinning; these authors, in considering Finetti *et al.*'s (2001) Middle Miocene-Pliocene lithospheric faults, geometrically estimated that a crustal antiformal stack 60 km thick should have been formed.

Thermal erosion is defined by the upward movement of the 1200°C isotherm, due to heating from the asthenosphere. Thermal erosion implies extension, and therefore according to Finetti *et al.*'s (2001) interpretation it would have been active only since the Pliocene. Heating from the asthenosphere can be modelled approximately using the heat transfer equation [*i.e.* parallel slab model: Carslaw and Jager, (1959)], given the thickness of the lithosphere at the end of the collisional stage, that is Pliocene, according to Finetti *et al.* (2001). These authors do not suggest any value for this parameter; however, even considering a thin lithosphere (60 km, *i.e.* half the thickness of a normal thermal lithosphere) and heated by a plume producing a sudden 300°C increase of basal temperature, thermal erosion alone is not able to determine the present lithospheric thickness, in the Pliocene-Present time span (Table 1 and Fig. 7). It derives that orogenic extension is necessary. However, estimations on the Pliocene-Present extensional strain rate indicate that it is very low (Bertini *et al.*, 1991; Carmignani *et al.*, 1994; Liotta, 1996; Dallmeyer and Liotta, 1998) and not sufficient to produce significant crustal thinning. The same point of view is shared by Finetti *et al.* (2001) who, apart from the seismogenetic Altotiberina structure (Boncio and Lavecchia, 2000), do not indicate other important normal faults. Consequently, orogenic extension must be considered active before the Pliocene.

Another point against a dominant compressional setting derives from the superimposition of the Ligurian Units on the Triassic evaporites and/or Palaeozoic phyllites. If the Tuscan Nappe omission were from out-of-sequence thrusting, the complete tectonic pile should be preserved at both the western and eastern boundaries of the tectonic depression (Fig. 8A) deriving from the thrust evolution (Fig. 6). By contrast, if boudinage determined the Tuscan Nappe omission, the western or eastern border of such a tectonic depression (depending on the sense of boudinage asymmetry) must be characterised by tectonic omission (Fig. 8B), such as for the case of southern Tuscany (Figs. 8C and 8D).

6. The CROP 18 seismic lines

The CROP 18 seismic survey represented, therefore, an opportunity to investigate the deep structures of Tuscany and to contribute to the reconstruction of the tectonic evolution of the inner

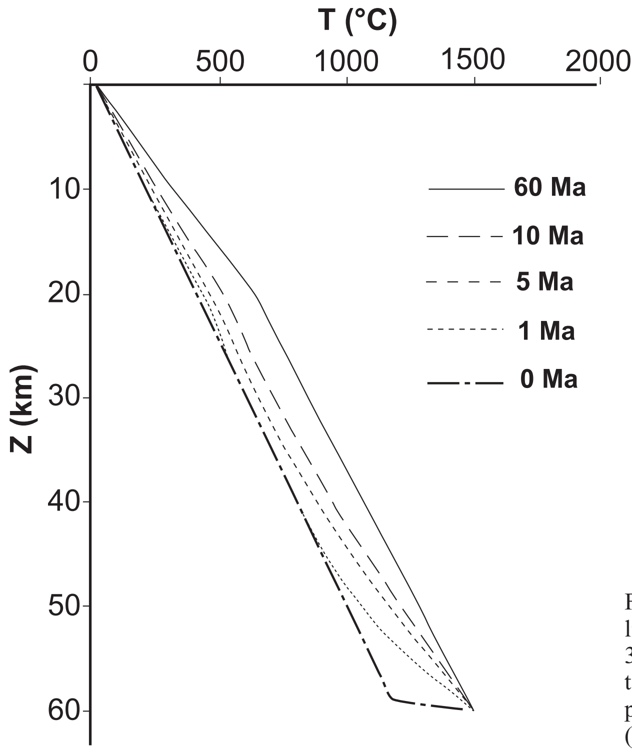

Fig. 7 - Temperature evolution of a 60-km thick lithosphere subject to a basal temperature increase of 300°C at T = 0°C. Numbers on geotherms represent time in Ma after basal heating. Geometry and parameters are listed in Table 1 [after Brogi *et al.* (2005d), redrawn].

Northern Apennines. Below, we give our interpretation of the CROP 18 seismic survey, as already presented in Brogi *et al.* (2005c, 2005d). This interpretation accepts the extensional framework, since extension offers a better explanation for the geological structures and the tectonic evolution of southern Tuscany.

The CROP 18 survey (Cameli, 1994) was acquired during 1995 and it is divided into two transects, named CROP 18A and CROP 18B (Fig. 1) which are roughly NNW-SSE oriented. These were recently reprocessed down to 10 s TWT reaching the crust-mantle transition (Accaino *et al.*, 2005a, 2005b).

Table 1 - Geometry and thermal parameters for the geotherms shown in Fig. 7. Symbols: K - thermal conductivity; A - heat production; TC - thermal capacity (after Brogi *et al.,* 2005d)

	Upper crust	*Lower crust*	*Lithosperic mantle*
Thickness (km)	10	10	40
K (W m^{-1} °C^{-1})	2.5	2.1	3.0
A (W m-3)	1.4	0.4	0.006
TC (MJ m^{-3} °C^{-1})	2.24	2.24	3.30

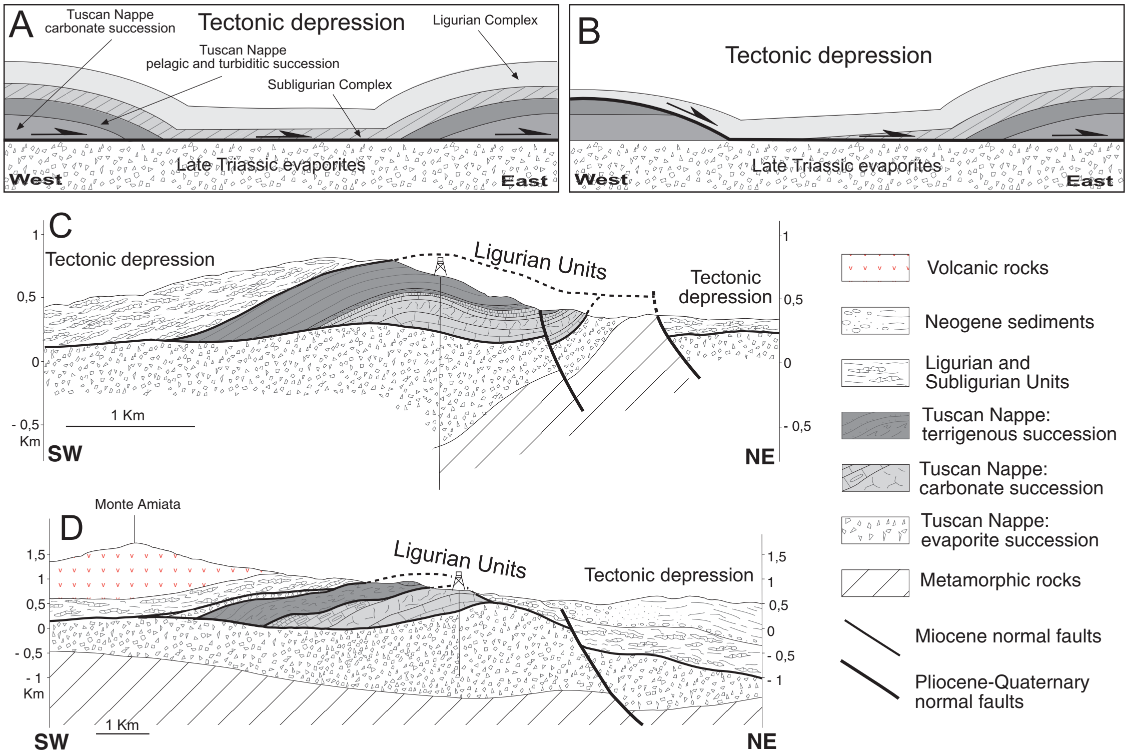

Fig. 8 - A) Enlargement of the tectonic depression given in Fig. 6, cartoon 4. Note that the out-of-sequence evolution implies preservation of the tectonic units pile on the shoulders of the syntectonic basin; B) idealised tectonic depression derived by asymmetric boudinage with top-to-east sense of shear. In contrast to (A), the western border of this tectonic depression is characterised by omission of tectonic units; note the cutoff relationship between the lower stratigraphic units of the Tuscan Nappe and the tectonic boundary, located at the base of the Ligurian Units. (C-D) Geological cross-sections from the Larderello and Mount Amiata geothermal areas, respectively. The structural relationships, as reconstructed from borehole and field data, are those shown in (B) [after Lazzarotto, (1967) and Calamai *et al*., (1970), redrawn; Brogi *et al.*, (2005c)].

Their geological interpretation was based on: a) geological cross-sections constructed along the traces of the seismic lines; b) data from deep boreholes close to the traces of the seismic profiles; c) commercial seismic profiles acquired for geothermal exploitation and crossing the CROP 18 lines. Since CROP 18A passes through the core of the Larderello geothermal area, where many geological and geophysical data are available, its geological interpretation is better constrained than that of the CROP 18B line. The line drawings of the unmigrated CROP 18 transects are shown in Figs. 9 and 10. The occurrence of out-of-plane, anomalous, events and sets of diffractions are considered useful in recognising lateral and/or vertical inhomogeneities, as expected in the Tuscan geothermal province, typified by systems of normal faults, widespread magmatism and fluids in fractured layers. Conversion from time to depth was obtained by taking into account the migrated sections and applying the average velocity fields (Accaino *et al.*, 2005b) given in Fig. 11. The deriving geological sections are shown in Fig. 12. More information on data processing, velocity analyses, depth conversion, migrated sections and geological data is in Accaino *et al.* (2005a, 2005b), Tinivella *et al.* (2005) and Brogi *et al.* (2005b).

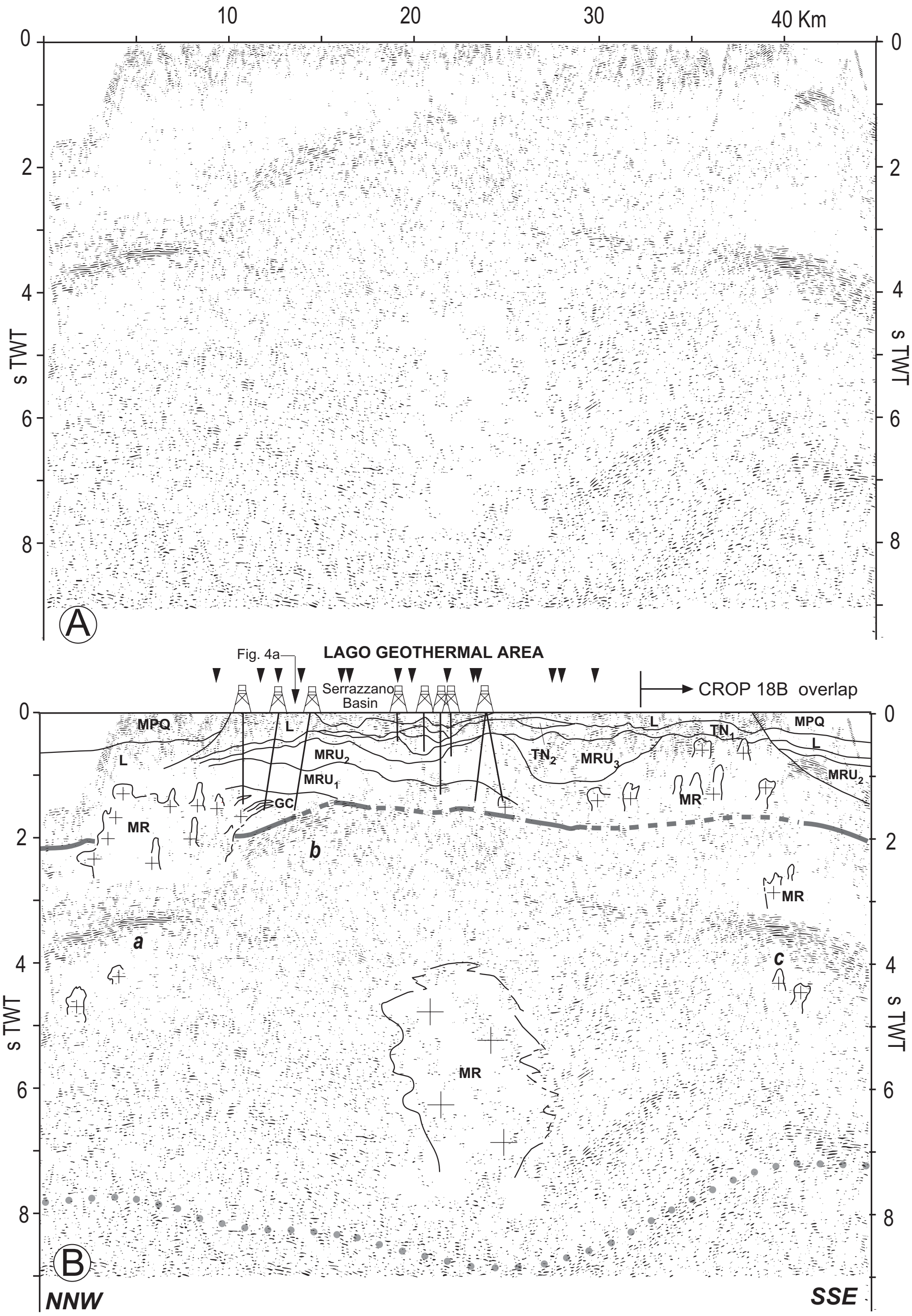

Fig. 9 - Line drawing of the unmigrated CROP 18A line (A) and its geological interpretation (B). The datum plane is 200 m above sea-level. Boreholes and intersections (black triangles) with previously acquired seismic lines are shown. The inclined wells are deviated. The stratigraphic and tectonic boundaries are shown by thin black lines. The thick grey line shows the K-horizon which was clearly identified considering also the intersection with other seismic lines; the dashed grey line shows the supposed lateral extension of the K-horizon. ***a***, ***b*** and ***c*** denote the reflection groups located below the K-horizon. Symbols such as in Fig. 3. The cross pattern denotes intrusive magmatic bodies. The crust-mantle transition is marked by the dotted line, and is located taking into consideration also data from seismic refraction lines (Giese *et al.*, 1981; Ponziani *et al.*, 1995).

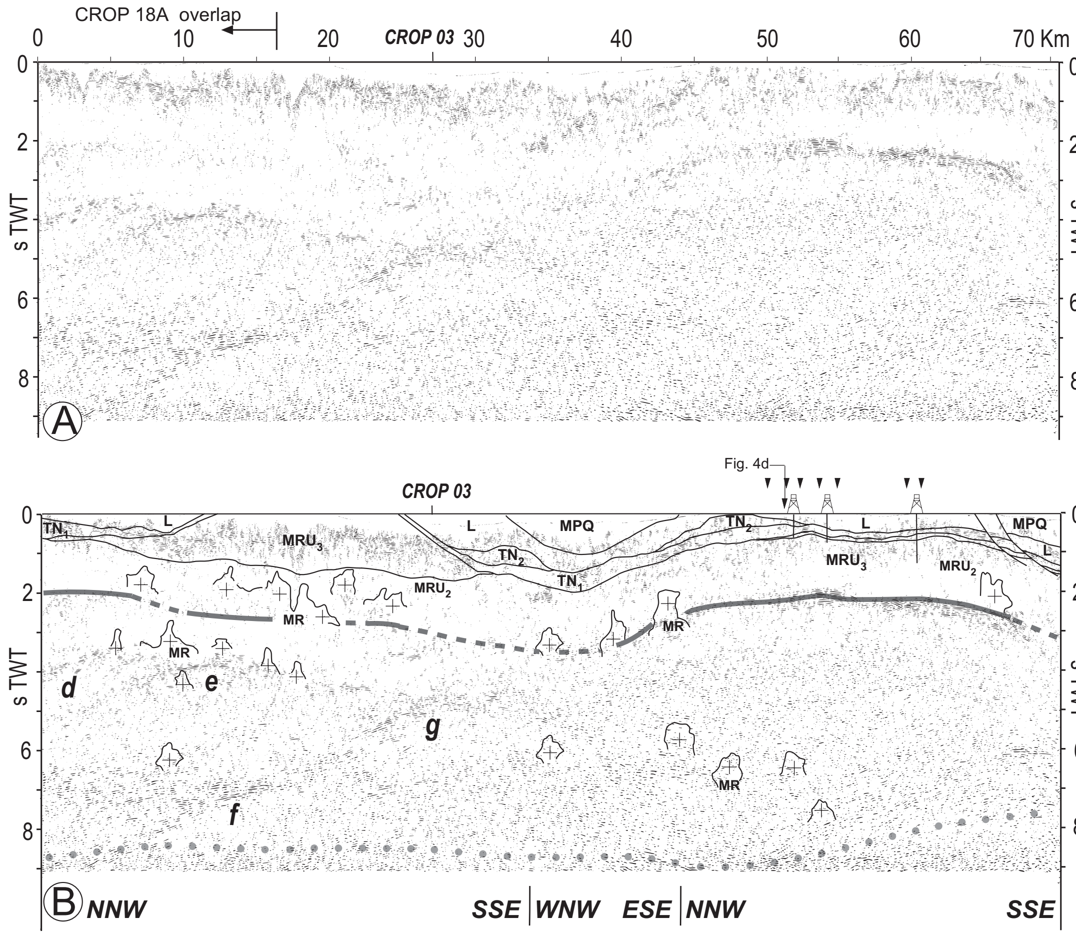

Fig. 10 - Line drawing of the unmigrated CROP 18B line (top) and its geological interpretation (bottom). The datum plane is 200 m above sea-level. ***d***, ***e***, ***f*** and ***g*** denote the reflection groups located below the K-horizon. Other information as in Fig. 9. Symbols as in Figs. 3 and 9.

7. The CROP 18A transect

This profile shows a scarcely reflective upper part where discontinuous reflections occur (Fig. 9). A reduced reflectivity is displayed in the northernmost part of the profile down to about 1.5 s TWT (≈ 3 km, Fig. 12A), where an area with homogeneous and low contrast of acoustic impedance (*i.e.* transparent area) is displayed. Although the transparency may be linked to technical reasons, local geothermal boreholes encountered Pliocene felsic magmatic rocks which strongly suggest an interesting correlation between granitoids, known as isotropic rocks, and the transparency in the seismic reflection data (Matthews, 1987). Similar considerations are also proposed for the other transparencies in the section, where gravimetric (Ricceri and Stea, 1993; Baldi *et al.*, 1995), teleiseismic (Foley *et al.*, 1992; Batini *et al.*, 1995) or magnetotelluric studies (Fiordelisi *et al.*, 1995) suggest the occurrence of magmatic bodies at depth (Figs. 9 and 12A). The K-horizon is indicated by weak amplitudes and is, laterally very discontinouous. Its identification

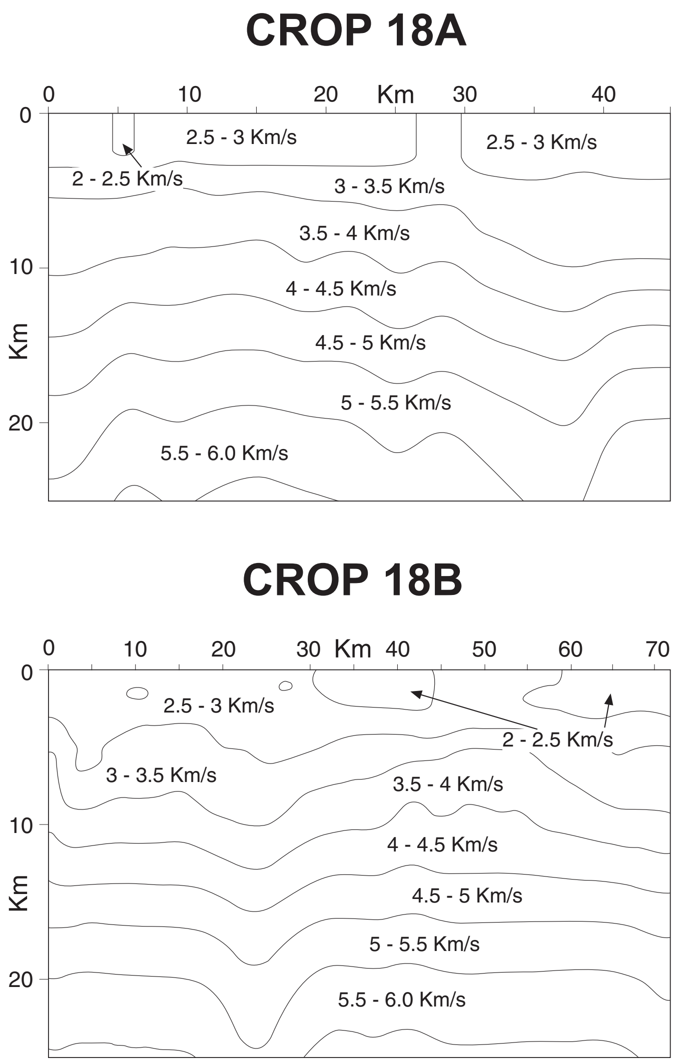

Fig. 11 - Regional average velocity fields used for the time-depth conversion [after Accaino *et al.*, (2005b), redrawn].

and location was obtained by considering intersections with previously acquired commercial seismic lines. On the whole, the K-horizon ranges between 1.5 and 2 sTWT (Fig. 9) corresponding to about 3-5 km (Fig. 12A). In the central part of the profile, where the highest heat flux in the Larderello area is recorded (Bellani *et al.*, 2004), the K-horizon reaches its shallower depth (Lago geothermal area, Figs. 9 and 12A). Three groups of prominent reflections are displayed below the K-horizon, between 2 and 4.5 s TWT. The shallower group (*b,* in Fig. 9) consists of northwest subparallel reflections better organised in the migrated section. The other two groups (*a* and *c*, Fig. 9) are located in the northern and southern parts of the profile and are typified by high-amplitude, flat-to-gently dipping, short reflections and correlated over small distances.

The base of the crust is not well imaged although discontinuous packages of high-amplitude reflections (7-9 s TWT, 22-24 km, Figs. 9 and 12A) may relate to the crust-mantle transition, according to refraction seismic data (Giese *et al.*, 1981; Ponziani *et al.*, 1995).

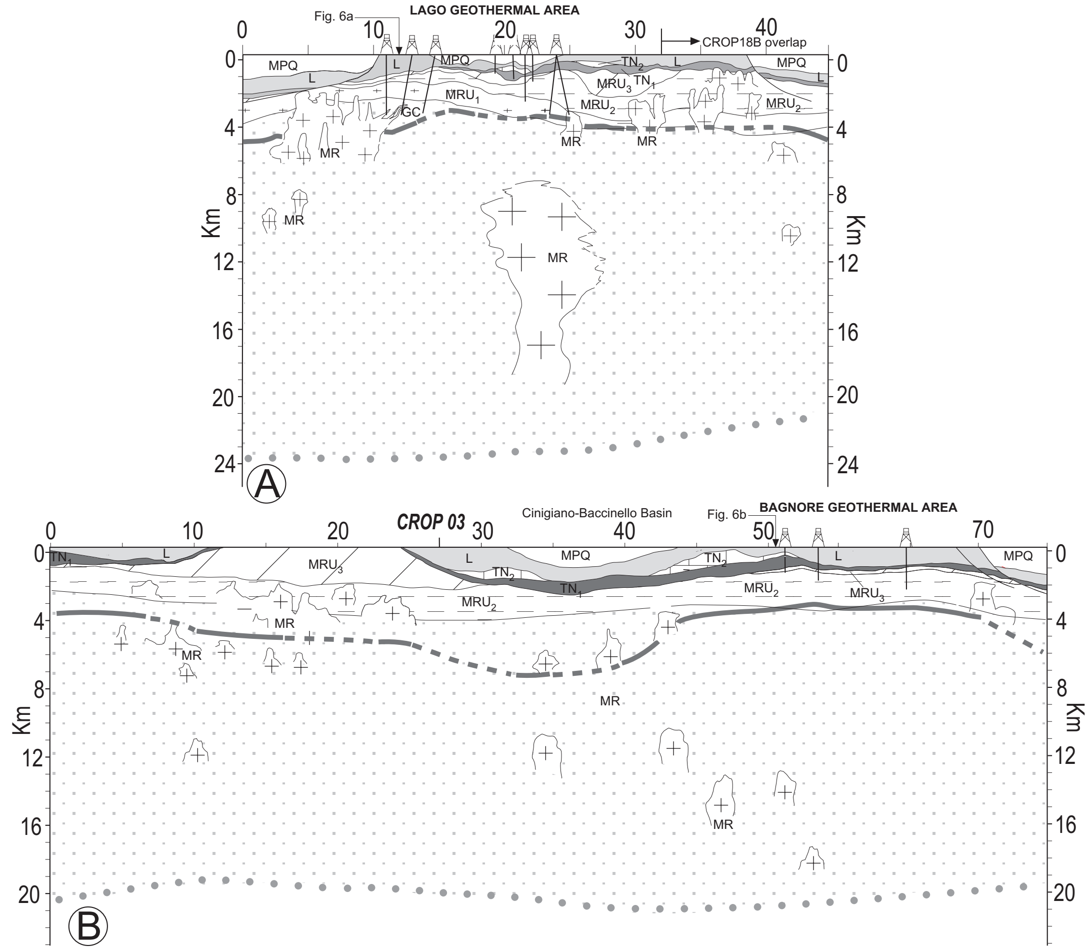

Fig. 12 - Geological cross-sections obtained from the interpretation of the CROP 18A (A) and 18B (B) lines. The dotted pattern indicates unresolved continental crust. Other symbols as in Fig. 3.

8. The CROP 18B transect

As in the CROP18A transect, the upper part of this profile is typified by a weak reflectivity. A wide area with low contrast in acoustic impedance (Fig. 10) is located between 1 and 2 s TWT (1.5-3.5 km, Fig. 12B) at the NW end of the section. This seismic signature accounts for granitoids at depth (Figs. 10 and 12B), as suggested by the outcrops of Pliocene volcanic and granitic rocks located close to the CROP 18B line (Fig. 1), in the Roccastrada area (Borsi *et al.*, 1965). Similar considerations are possible in the southernmost part of the section (about 1.5 - 2.5 sTWT, Fig. 10). Other areas with low contrast of acoustic impedance are located at mid-lower crustal levels: these are explained as magmatic bodies, probably emplaced during the Pliocene-Quaternary time span (Figs. 10 and 12B). The K-horizon ranges in depth between 2 and 3.5 s TWT (about 4-7 km, Figs. 10 and 12B), showing a deeper location below the Cinigiano-Baccinello Miocene Basin (Figs. 1, 10, 12B). The K-horizon has weak reflecting amplitudes in

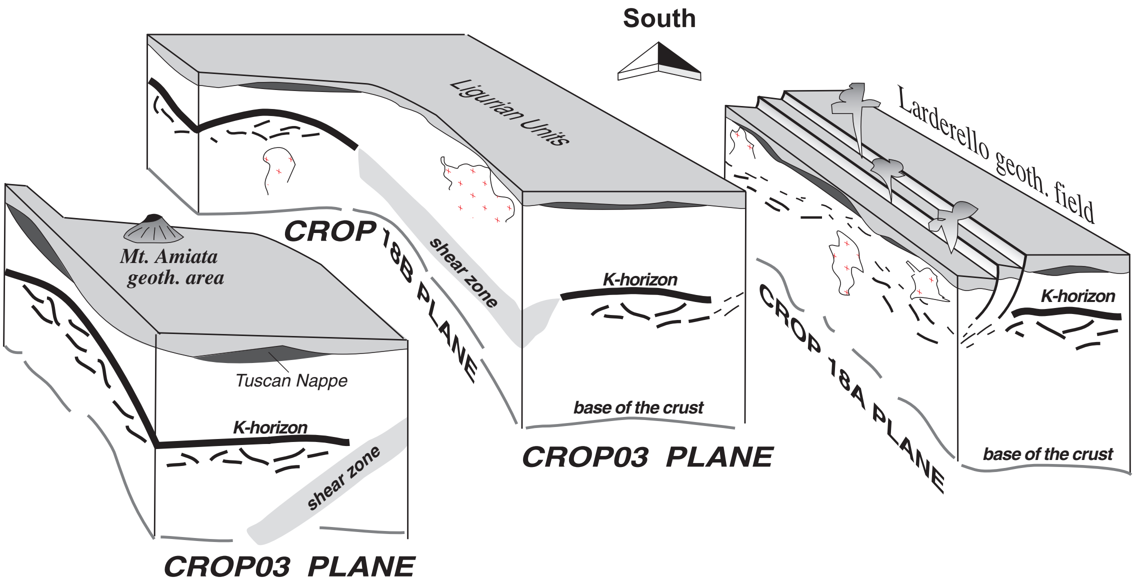

Fig. 13 - Structural sketch illustrating the control of the crustal shear zones on the reflectivity of the CROP 18 profiles. The reflectivity of the K-horizon and reflections below it are shown by the thickness of the lines (after Brogi *et al.,* 2005c). Not to scale.

the northwestern part of the section where it was identified mainly by means of the overlap with the CROP 18A transect (Figs. 1 and 10). By contrast, in the southeastern part of the section, underneath the Mt. Amiata geothermal area, the K-horizon shows a prominent reflectivity (Fig. 10). Here, below the K-horizon, highly reflective groups of reflections are located (Fig. 10), both in the unmigrated and migrated profiles. At deeper levels, other groups of reflections are defined by northwestward dipping packages of high-amplitude and poor subparallel reflections (*d*, *e*, *f* and *g* in Fig. 10). After migration, these groups are better organised, more inclined to the north and slightly moved to the south. The base of the crust is highlighted by rather discontinuous groups of strong reflections at about 7-8 s TWT (about 20-22 km, Figs. 10 and 12B).

9. Discussion

The reflectivity of the CROP18 lines is similar to that of other crustal lines acquired in geothermal provinces affected by crustal extension. These seismic lines generally display poor reflectivity in the upper crust and, by contrast, high degrees of reflectivity in the mid-lower crust. The partition between these two seismic facies is usually clear. This is the case of the Rhine Graben (Mayer *et al.*, 1997) and the Colorado area (Hamilton, 1987; Lucchitta, 1990), but it is also the case of southern Tuscany, where the boundary between the upper and mid-lower crust is marked by the K-horizon, as shown by commercial profiles (Cameli *et al.*, 1993) and by the CROP 03 crustal seismic line (Liotta *et al.*, 1998). By contrast, the CROP 18 lines show widespread poor reflectivity, apart from groups of good reflections at depth (*a*-*g* in Figs. 9 and 10).

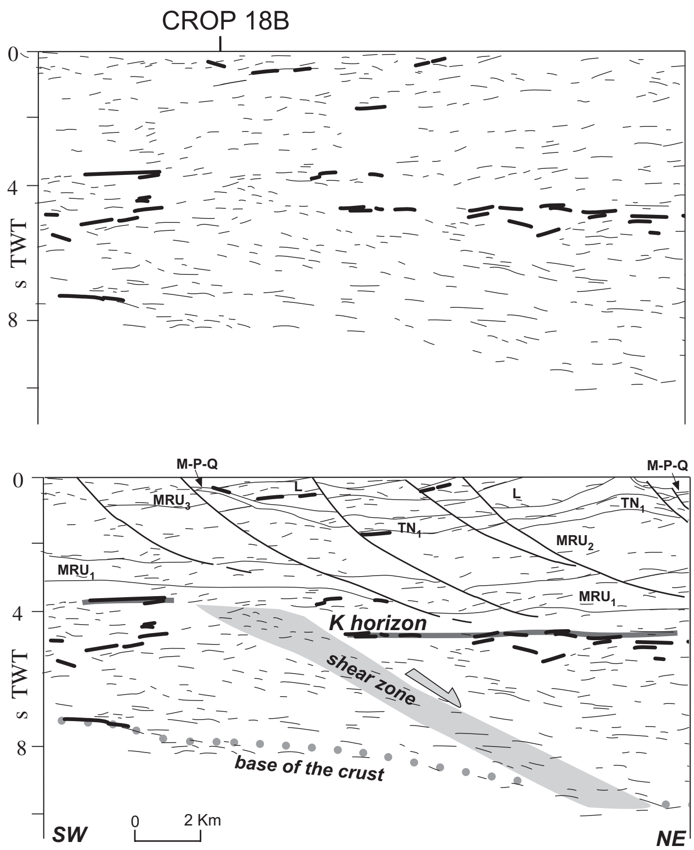

Fig. 14 - Line drawing (top) and its geological interpretation (bottom) of the CROP 03 crustal seismic line where it intersects the CROP 18B line. See also Fig. 1. Thick lines indicate the more prominent reflections. Other symbols as in Fig. 3 [after Liotta *et al.*, (1998), redrawn; Brogi *et al.*, (2005c)].

The geological interpretation of both CROP 18 transects shows that the upper part of the crust is characterised by isolated geological bodies of the Tuscan Nappe and Verrucano Group. This information, joined with the CROP 03 results (Decandia *et al.*, 1998), field and borehole data (Calamai *et al.*, 1970; Lazzarotto and Mazzanti, 1978; Lazzarotto, 1967; Bertini *et al.*, 1991) indicate that the boudinage is a regional feature in southern Tuscany.

As regards the CROP 18A line, the poor reflectivity may be linked to the direction of the seismic profile which crosses one of the most important extensional shear zones of the Larderello area (Fig. 5). This shear zone is seismically characterised by NE-dipping weak reflections, by the loss of K-horizon reflectivity and of the lozenge-shape markers (Fig. 5). Assuming trapped fluids as the origin for the seismic signature at the brittle-ductile transition, the loss of reflectivity can be explained by fluid escape, throughout the brittle shear zone (Brogi *et al.*, 2003).

Since CROP 18A is oriented approximately along the shear zone strike, it derives that its reflectivity results necessarily scarce down to the brittle/ductile transition (Figs. 9 and 13).

Similar seismic features characterise the CROP 18B line. In the central part of this section, the loss of the K-horizon reflectivity is related to the intersection with a crustal shear zone, affecting the lower part of the crust and highlighted by the CROP 03 survey (Figs. 13 and 14). The loss of K-horizon reflectivity on the CROP 03 plane makes it difficult to locate this seismic

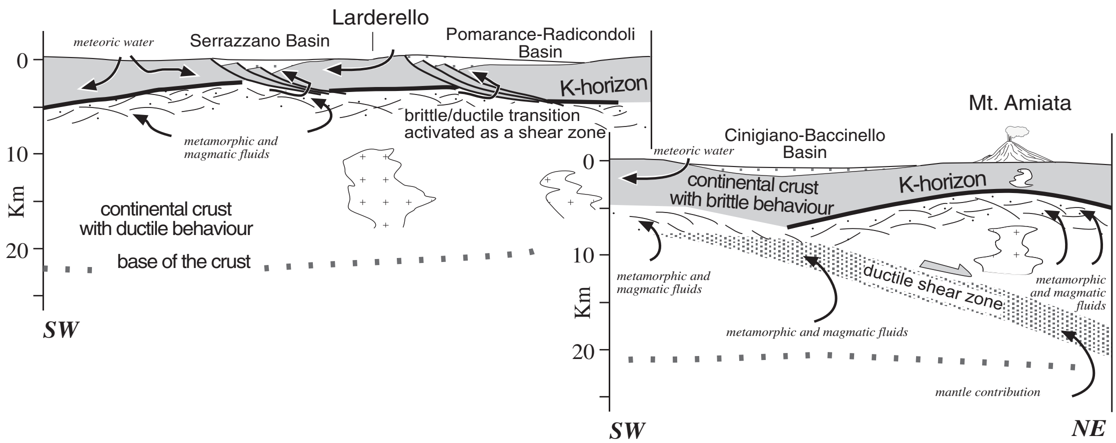

Fig. 15 - Geological interpretation of crustal structures in southern Tuscany. The occurrence of coeval extensional shear zones, active in the brittle and ductile parts of the crust, is shown. Grey arrow: sense of shear in the lower crust shear zone. The thin black arrows indicate schematic pathways for meteoric, magmatic, metamorphic fluids and isotopic mantle elements, all of them discovered in the geothermal fluids sampled in the Larderello and Mount Amiata area (Magro *et al.*, 2003). Following Bellani *et al.* (2004), the brittle shear zones of the Larderello area, are affected by convective heat transfer (after Brogi *et al.*, 2005c).

marker on the CROP 18B plane. Consequently, the lateral extension of the K-horizon (dashed line in Fig. 10) is weakly constrained and its depth might be greater (reasonably down to 0.5 TWTs below the dashed line) in the central part of the CROP 18B line.

In contrast, the typical K-horizon seismic facies, characterised by bright spot features, is displayed in the central-southern part of the profile where the plane of the survey changes direction (Figs. 1, 10 and 13).

The nature of the deep reflections (*a-g*, in Figs. 9 and 10), Tinivella *et al.* (2005) and Accaino *et al.* (2005b), based on Amplitude Versus Offset analyses and seismic velocity models, suggest that these could be related to fluids and/or lithological contrasts. Both possibilities are suitable in the framework of a highly extended continental crust. In this tectonic framework, trapped fluids in shear zones or mafic intrusions from the mantle could explain the observed deep reflectivity. Furthermore, Tinivella *et al.* (2005) indicate possible vertical channels of magmatic intrusions crossing the lower crust and emplaced in the upper crust.

The crust-mantle transition is not well imaged in the CROP 18 lines, probably for its along-strike orientation.

10. Conclusions

The continental crust of southern Tuscany is assumed to be affected by extensional tectonics since Early-Middle Miocene, being alternative hypotheses unable to explain geological features of the first order, such as the present crust and lithospheric mantle thicknesses.

Previous studies on the CROP 03 survey highlighted crustal shear zones affecting both the upper and mid-lower crust of southern Tuscany (Barchi *et al.*, 1998; Decandia *et al.*, 1998; Lavecchia *et al.*, 2004). The crustal brittle shear zones of the Larderello area are characterised by a fair reflectivity, down to the brittle/ductile transition (Brogi *et al.*, 2003). Since the CROP 18A plane crosscuts along strike one of these shear zones, its reflectivity is generally weak. Consequently also the K-horizon, that is usually a clear mid-crustal marker, results discontinuous and difficult to detect without information from commercial seismic reflection lines, differently oriented and intersecting the CROP 18A plane. The relationship among brittle shear zone, reflectivity and orientation of the CROP18A line is sketched in Fig. 13.

CROP 18B, as previously mentioned, shows a similar weak reflectivity in its northern sector, partly related to magmatic bodies at depth. No other seismic reflection lines investigate this part of southern Tuscany. However, the CROP 18B reflectivity is influenced by the intersection with the mid-lower crust shear zone, displayed in the CROP 03 line, and typified by a fair seismic signature (Fig. 13 and 14).

In conclusion, the integration between the CROP 18 and 03 lines permitted us to recognise two levels of crustal shear zones, located above and below the brittle-ductile transition, respectively (Fig. 15). Bellani *et al.* (2004) suggested that preferential pathways for the flow of mixed meteoric and deep fluids of magmatic and metamorphic origin can be localised in the brittle shear zone of the Larderello area. The occurrence of isotopic mantle elements within the geothermal fluids (Magro *et al.*, 2003) implies channels for their upward migration. The deep shear zones in the crust of southern Tuscany can represent possible pathways from the lower to the upper crust through the brittle/ductile transition, operating as a crustal shear zone. Finally, the occurrence of crustal widespread magmatism (Brogi *et al.*, 2005c, 2005d; Tinivella *et al.*, 2005) can provide the best mechanism to transfer heat from depth to shallower crustal levels. If shear zones interact with deep magmatic melts, a further source for mantle elements will be provided.

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