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Line CROP 18: Southern Tuscany
La linea CROP 18: Toscana Meridionale

BATINI F. ([1]), CAMELI G.M. ([1]), LAZZAROTTO A. ([2]), LIOTTA D. ([3])

ABSTRACT - The reflection crustal seismic line CROP 18 was acquired to investigate the relationship between the structure of the continental crust and the geothermal resources of southern Tuscany. The structural setting of southern Tuscany derives from two different and contrasting deformational processes: the first one is connected to the convergence and subsequent collision between the European and African margin (Late Cretaceous - Early Miocene); the second process is instead connected to the extensional tectonics which affected the inner part of the Northern Apennines since Miocene. Extensional tectonics is joined with emplacement of granitoids deriving by mixing of crustal and mantle magmas. Southern Tuscany is presently characterised by high heat flow: 120 mW/m^2 on average, with local picks up to 1000 mW/m^2. The reflection seismic lines acquired for geothermal purposes highlighted a regional mid-crustal reflector, referred to as K-horizon, with bright spot features. The crust-mantle and lithoshere-asthenosphere boundaries are located at 22-25 km and about 30 km, respectively.

KEY-WORDS: Southern Tuscany, reflection seismic, deep crust, geothermal resources.

RIASSUNTO - La linea sismica a riflessione CROP 18 è stata realizzata per indagare le relazioni fra struttura della crosta continentale e risorse geotermiche nella Toscana meridionale. L'assetto strutturale della Toscana meridionale deriva da due diversi ed opposti processi deformativi: il primo collegato alla convergenza e successiva collisione fra il margine europeo e quello africano (Cretaceo sup. - Miocene inf.); il secondo invece collegato alla tettonica distensiva che a partire dal Miocene inferiore e medio ha interessato la parte interna dell'Appennino settentrionale. La tettonica distensiva è accompagnata, nella Toscana meridionale, dalla messa in posto di corpi magmatici, di età neogenico-quaternaria, i quali principalmente derivano da fenomeni di mescolamento fra fusi di origine infra-crostale e mantellica. L'intera Toscana meridionale è caratterizzata da elevato flusso termico con picchi in corrispondenza delle aree geotermiche fino a 1000 mW/m^2. Le linee sismiche a riflessione hanno messo in evidenza un riflettore medio-crostale, ritenuto di importanza regionale, noto come orizzonte K, che talvolta si presenta con caratteristiche di bright spot. Il passaggio crosta-mantello è ritenuto collocarsi ad una profondità di 22-25 km mentre il passaggio litosfera-astenosfera è stimato a circa 30 km di profondità.

PAROLE CHIAVE: Toscana meridionale, sismica a riflessione, crosta profonda, risorse geotermiche.

([1]) Enel Green Power, Via Andrea Pisano,120 - 56122 Pisa.
([2]) Dipartimento di Scienze della Terra, Università di Siena, Via Laterina, 8 - 53100 Siena.
([3]) Dipartimento di Geologia e Geofisica, Università di Bari, Via Orabona, 4 - 70125 Bari.

1. – 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 & Guazzone, 1972; Boccaletti *et alii*, 1981) of the Adria and European plates, represented by the Sardinia-Corsica massif (Late Cretaceous-Early Miocene); the second related to the extensional tectonics occurring since the Early-Middle Miocene (Carmignani & Kligfield, 1990; Jolivet *et alii*, 1990; Bertini *et alii*, 1991; Baldi *et alii*, 1994b; Carmignani *et alii*, 1994, 1995; Jolivet *et alii*, 1998). This extension migrated eastwards, affecting the entire inner part of the northern Apennines: the opening of the northern Tyrrhenian Basin is the clearest evidence of this extensional tectonics (Carmignani *et alii*, 1994). Extension resulted in the development of the 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 alii*, 1987). They exhibit different degrees of extension, this being greater in the southern sector, i.e. southern Tuscany; here, extensional tectonics is accompanied by the emplacement of Neogene-Quaternary magmatic bodies, mainly derived from mixing of crust and mantle magmas (Serri *et alii*, 1993). Southern Tuscany is characterised by an average altitude of 270 meters, positive Bouguer anomalies (Elter *et alii*, 1975; Giese *et alii*, 1981) and high heat flow: 120 mW/m^2 on the average, (fig. 2) with local peaks up to 1000 mW/m^2 (Mongelli *et alii*,1989; Mongelli & Zito, 1991). Two important geothermal systems are located in southern Tuscany: the Larderello and the Monte Amiata geothermal fields, to the north and to the south, respectively (fig. 2).

The crust-mantle passage, in Southern Tuscany, is thought to be at a depth of around 22-25 km (Giese *et alii*, 1981; Locardi & Nicolich, 1992; Ponziani *et alii*, 1994; Decandia *et alii*, 1998), while the lithosphere-asthenosphere boundary is believed to be at about 30 km (Catalano & Panza, 1981; Decandia *et alii*, 1998).

2. - GEOLOGICAL FRAMEWORK

The regional tectono-stratigraphic units (fig. 3) of southern Tuscany include:

1) Miocene-Pliocene sediments that unconformably overlie previously deformed strata. These sediments fill the Miocene and Pliocene extensional tectonic depressions of Southern Tuscany. The sedimentary sequence is comprised of: late Tortonian-Messinian lacustrine sediments; Messinian marine and "lac-mer" deposits; two different sequences of marine sediments (Early and Middle Pliocene, Bossio *et alii*,1993);
2) late Burdigalian- early Tortonian marine sediments which unconformably rest on the Ligurian Units (Sestini, 1970; Bossio *et alii*, 1993);
3) a Ligurian Complex composed of Middle and Late Jurassic ophiolites, Late Jurassic radiolarites, Early Creataceous pelagic sediments and a Cretaceous-Middle Eocene flysch series. This complex was thrust eastward over the Tuscan facies complex during the Late Oligocene-Early Miocene collisional stage;
4) the Tuscan Complex includes sedimentary rocks which range in age from Late Triassic to Late Oligocene-Early Miocene. These reflect the transition from a lagoonal environment (Late Triassic evaporites: Burano Formation), to a carbonatic platform (Rhetian, earliest Jurassic), to a pelagic environment (Jurassic-Oligocene), to a foreland syn-orogenic basin, where an Oligocene-Early Miocene arenaceous flysch deposited. The sedimentation was interrupted by the overthrusting of the Ligurian Units, during Late Oligocene-Early Miocene. In this time period, the Tuscan complex was tectonically detached and translated eastward (Tuscan Nappe) along a detachment surface located in the Triassic evaporites.

The substrate of the sedimentary cover is mainly known by drilling of deep geothermal wells, carried out in the Larderello and Amiata zones. It is composed of two units (Bertini *et alii*, 1991): an upper one referred to as the Monticiano-Roccastrada Unit and a lower one corresponding to the Gneiss Complex. The Monticiano-Roccastrada Unit consists of three metamorphic groups:

1) quartz meta-conglomerates, quartzite and phyllite (Verrucano Group, Early-Middle Triassic), sandstone, phyllite (Middle, Late Carboniferous-Permian). These rocks are involved in duplex structures with the Triassic evaporites (MRU3 in fig. 3);
2) a Palaeozoic phyllite-quartzitic Group (MRU2 in fig. 3);
3) a Palaeozoic Micaschist Group (MRU1 in fig. 3).

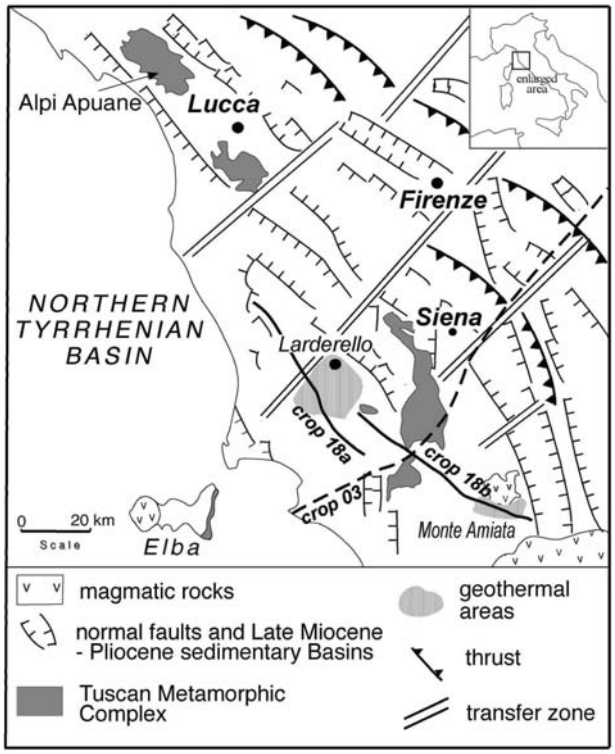

Fig. 1 - Simplified structural map of inner portions of the Northern Apennines illustrating the main features associated with extensional tectonics and the trace of the CROP O3 and CROP 18 profiles.

- Carta strutturale semplificata della parte interna dell'Appennino settentrionale: sono indicate le principali strutture associate con la tettonica distensiva e la traccia delle linee sismiche CROP 03 e CROP 18

These three groups were affected by Alpine greenschist metamorphism: the last two groups appear to have Silurian-Early Carboniferous protoliths (Puxeddu, 1984; Elter & Pandeli, 1990).

In contrast to the Monticiano-Roccastrada Unit, the effects of the Alpine orogeny are not recorded in the Gneiss Complex. The Monticiano-Roccastrada Unit and the Gneiss complex are separated by a ductile shear zone. The Gneiss complex is considered part of the continental crust, which was not involved in the Alpine orogeny (Elter & Pandeli, 1990) and therefore it was explained as a part of the Apennine foreland crust (Bertini *et alii*, 1991). In the Gneiss Complex, and in the micaschists and phyllites a later static high temperature/low pressure (HT/LP, below) metamorphism was superimposed on previous mineral associations (Del Moro *et alii*, 1982; Puxeddu, 1984). Studies of borehole petrology have recognized HT/LP conditions in the basement rocks (Del Moro *et alii*, 1982; Villa & Puxeddu, 1994). Magmatic intrusions were encountered by geothermal deep boreholes (Villa *et alii*, 1987).

The extensional structures of southern Tuscany have been described by Bertini *et alii* (1991) and Carmignani *et alii* (1994). In figure 4 three different extensional stages (Baldi *et alii*, 1994; Dallmeyer & Liotta, 1998) affecting the Larderello geothermal area are shown. The first one involved superimposition of the Ligurian Units, the structurally highest units in the nappe succession, along low angle normal faults (Lavecchia *et alii*, 1984), mainly over late Triassic evaporites (fig. 4/c). These faults flatten into the late Triassic evaporites, which comprise the main detachment level. This first extensional event occurred in the Burdigalian-Langhian on the basis of both stratigraphic considerations (Baldi *et alii*, 1994a, Carmignani *et alii*, 1994, 1995) and mineral cooling ages related to the exhumation of the Alpi Apuane core complex (Kligfield *et alii*, 1986; Carmignani & Kligfield, 1990).

The second extensional event occurred in a period between the Serravallian and the late Messinian. This event was characterised by normal faults which terminate downward in Paleozoic phyllites (Fig.4/b). The time of the beginning of the second extensional stage is not well constrained, but it must have been post-Langhian and pre-Pliocene (Baldi *et alii*, 1994a; Dallmeyer & Liotta, 1998). The third extensional event (fig. 4/a) was characterised by formation of high-angle normal faults which dissect early-middle Pliocene sediments and all the previous structures.

3. - OTHER GEOPHYSICAL DATA.

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 alii*, 1993). The top of the lower part is indicated by a discontinous reflector of high amplitude, referred to as the K-horizon (Batini *et alii*, 1978), which has local bright spot features (Batini *et alii*, 1985). The K-horizon often bounds a facies with strong convergent and divergent reflections and lozenge shaped geometry (Batini *et alii*, 1978; Cameli *et alii*, 1993). In the Larderello area, normal faults of the third extensional event tend to flatten in the K-horizon or inside the lozenge-shaped facies (Bertini *et alii*, 1991; Baldi *et alii*, 1994a; Cameli *et alii* 1993; 1998). Most local earthquakes are located within the lozenge-shaped

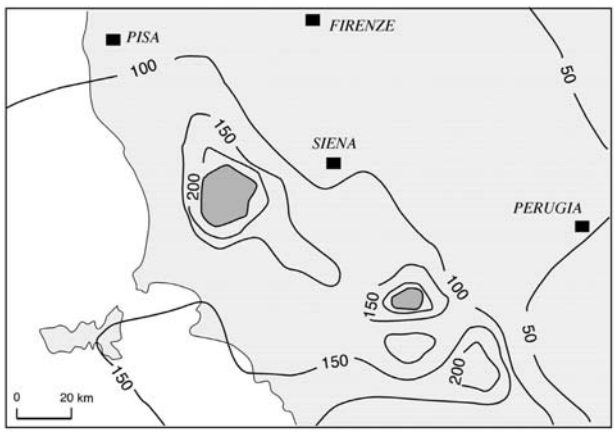

Fig.2 - Simplified heat flow map of southern Tuscany. Contour lines are in mW/m^2. Grey areas indicate the Larderello area, to the North, and the Monte Amiata area, to the South. (after MONGELLI *et alii*, 1989 and MONGELLI & Zito, 1991; modified).

- Carta semplificata del flusso di calore nella Toscana meridionale. Le isolinee sono in mW/m^2. Le aree in grigio corrispondono alla zona di Larderello, a Nord, ed alla zona del Monte Amiata, a Sud (da MONGELLI et alii, 1989 e MONGELLI & ZITO, 1991; con modifiche).

facies which is at a depth of 4-6 km, in the Larderello and Amiata areas; furthermore the hypocentral events abruptly decrease at deeper levels and rarely exceed a depth of 10 km (CAMELI *et alii*, 1993; 1998). Measurements of bottom hole temperatures suggest values ranging from 400°C to 450°C at the depth of the K-horizon depth (BERTINI *et alii*, 1991; CAMELI *et alii*, 1998). The K-horizon is deeper where the heat flow is smaller, suggesting a close relationship between heat flow and K-horizon depth (BALDI *et alii*, 1994a; CAMELI *et alii*, 1998). A delay in the propagation of the P waves, at a depth greater than 8 km, has been recognised by FOLEY *et alii* (1990), in the geothermal area of Larderello.

4. - SIGNIFICANCE OF THE CROP 18 SURVEY

Extensional tectonic environments characterised by high thermal flow, magmatism and uplift are often affected by geothermal systems (MUFFLER & DUFFIELD, 1995), as is the case of southern Tuscany. All geothermal areas show common characteristics such as: local seismicity gathered in levels next to the surface, interaction between meteoric fluids and fluids of deep origin; relatively small depth of the Moho; attenuation of the velocity of the P seismic waves and gravimetric anomalies outstanding structural levels and/or geologic bodies having lesser density. Neverthless the mechanisms and processes that control the interactions between those different aspects, briefly listed above, and the circulation of hydrothermal fluids, are still poorly understood (MUFFLER & DUFFIELD, 1995). The great amount of data collected (borehole measures, stratigraphic, petrographic and geochemical data, geological and geophysical surveys) makes southern Tuscany and the geothermal areas of Larderello and the Mt. Amiata a unique natural

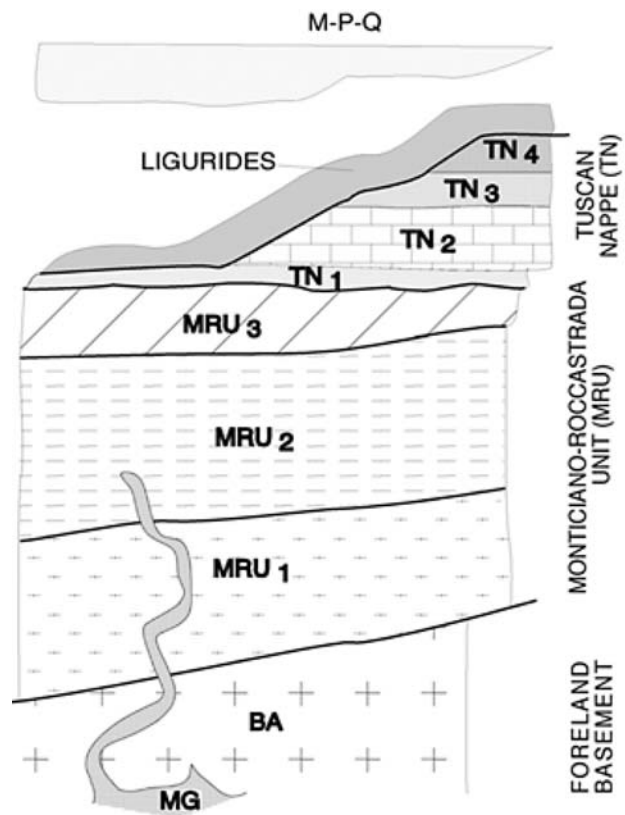

Fig.3 - Relationship between tectono-stratigraphic units recognized in southern Tuscany: MPQ - Quaternary, Pliocene and Miocene sediments; Tuscan Nappe (TN): TN4 - arenaceous flysch (late Oligocene-early Miocene); TN3 - terrigeneous pelagic sequence (Cretaceous-Oligocene); TN2 - carbonatic pelagic and platform sequence (Rhaetic-Jurassic); TN1- evaporites (late Triassic, Burano Formation); Monticiano Roccastrada Unit (MRU): MRU3 - Mesozoic-Paleozoic Group; MRU2 - phyllite-quartzitic group; MRU1 - paleozoic Mica-schist group; BA - Gneiss Complex; MG - magmatic intrusions. The boundary between the Ligurian Units and the substrate resulted from the Miocene extensional tectonics. (after BALDI *et alii*, 1994b, modified).

- Relazioni fra le unità tettono-stratigrafiche riconosciute nella Toscana meridionale. MPQ - sedimenti del Quaternario, del Pliocene e del Miocene; Falda Toscana (TN): TN4 - flysch arenaceo (Oligocene superiore-Miocene inferiore); TN3 - successione pelagica e terrigena (Cretaceo-Oligocene); TN2 - successione pelagica carbonatica e successione di piattaforma (Retico-Giurassico); TN1- evaporiti (Trias superiore, F. di Burano); Unità di Monticiano-Roccastrada (MRU): MRU3 - Gruppo Mesozoico-Paleozoico; MRU2 - Gruppo filladico-quarzitico; MRU1 - Gruppo dei micascisti ; BA - Complesso degli Gneiss; MG - intrusioni magmatiche (modificato da BALDI et alii*, 1994b).*

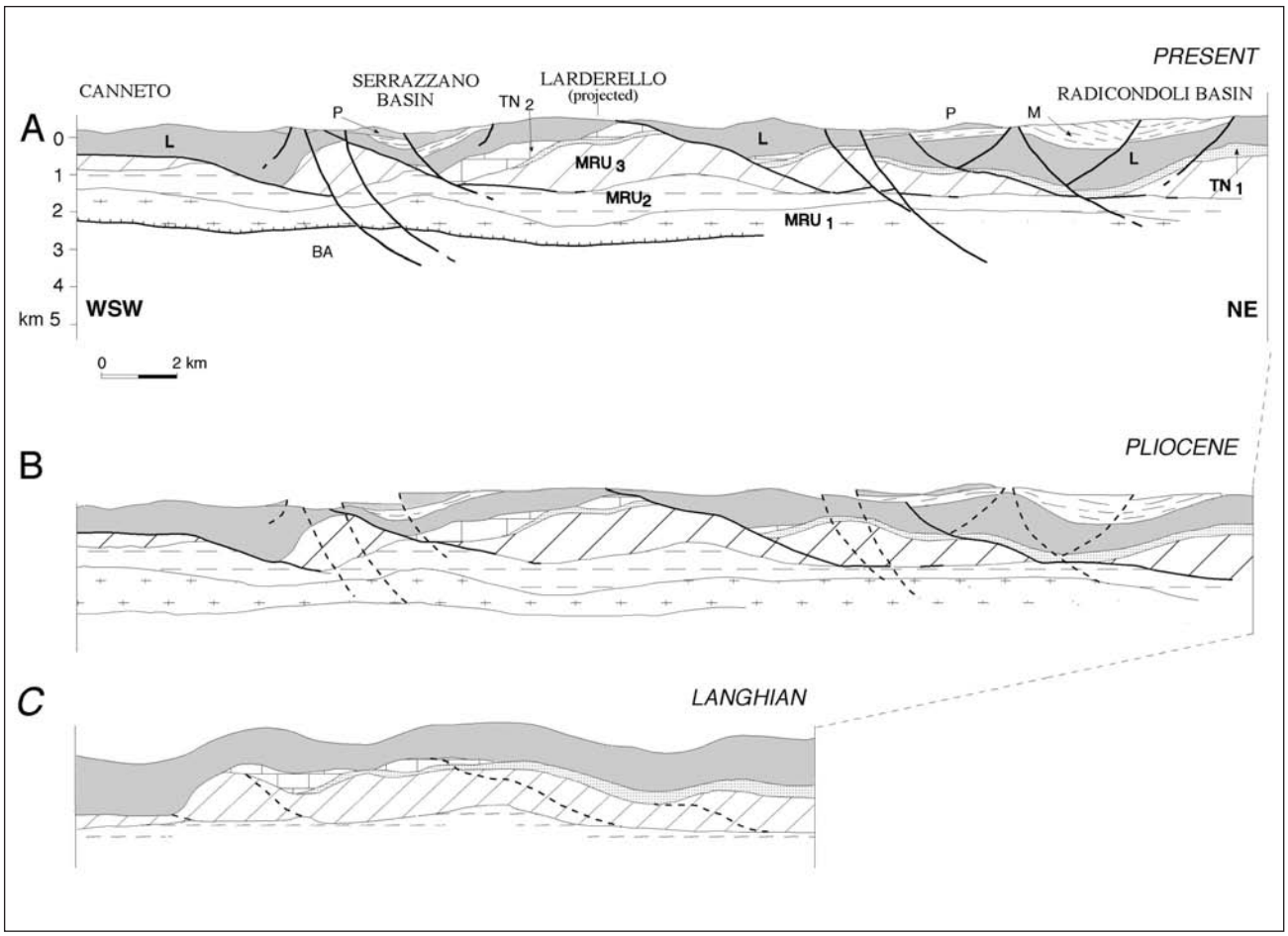

Fig.4 - (a) Geological cross section through the Larderello geothermal field (based on borehole stratigraphy, reflection seismic lines and field mapping). (b) Reconstructed Pliocene geological section. Note that late Miocene sediments are preserved in tectonic depressions defined by synsedimentary normal faulting related to the second extensional event; early and middle Pliocene sediments unconformably overlie late Miocene sediments which were deformed during deposition. During the second extensional event, exhumation of deepest rocks occurred; (c) Reconstructed Langhian geological section assuming no change in kinematic vectors during post-collisional 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 complex, 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 (modifed after BALDI *et alii*, 1994b, and DALLMEYER & LIOTTA, 1998).

- (a) Sezione geologica attraverso il campo geotermico di Larderello (basata sulla stratigrafia dei pozzi, su sezioni sismiche a riflessione e su rilevamenti geologici di superficie). (b) Sezione geologica retrodeformata che ricostruisce l'assetto strutturale al Pliocene. Notare che i sedimenti del Miocene superiore sono conservati nelle depressioni strutturali delimitate dalle faglie dirette sinsedimentarie attive durante il secondo evento distensivo; i sedimenti del Pliocene medio ed inferiore giacciono discordanti sui sedimenti miocenici, deformatesi durante la deposizione. Durante il secondo evento distensivo è avvenuta l'esumazione delle rocce strutturalmente più profonde; (c) Sezione geologica retrodeformata che ricostruisce l'assetto strutturale al Langhiano assumendo che la direzione del trasporto tettonico non abbbia subito variazioni durante lo sviluppo della tettonica distensiva post-collisionale. Si assume che non siano avvenute variazioni di lunghezza nei corpi geologici appartenenti al Gruppo Mesozoico-Paleozoico o nella parte carbonatica e terrigena della Falda Toscana; si assume inoltre che non siano avvenute variazioni volumetriche nei corpi geologici appartenenti alle Liguridi s.l., alle evaporiti triassiche, al Gruppo filladico-quarzitico ed al Gruppo dei Micascisti. Le sezioni relative al Pliocene ed al Langhiano sono state ricostruite considerando l'attuale livello del mare come riferimento (da BALDI et alii, 1994b e da DALLMEYER & LIOTTA, 1998; con modifiche).

laboratory for studying the relationships between the structure of the continental crust, magmatism and hydrothermal systems. Therefore, the CROP 18 profile was acquired in order to investigate the relationship between the extensional crustal structures of southern Tuscany and the main Italian geothermal resources, located in the Larderello and Monte Amiata geothermal fields. The line, NNW-SSE oriented, is divided in two parts (fig. 1): the northern part, named CROP 18/A profile, and the southern part, named CROP 18/B. The latter crosscuts the CROP 03 profile.

The CROP 18 geophysical results are under study. The geological interpretations will be presented in a forthcoming dedicated meeting. The related papers will be published in a special volume, edited by the Italian Geological Society.

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