by Fausto Batini¹, Andrea Brogi², Antonio Lazzarotto³, Domenico Liotta⁴, and Enrico Pandeli^{5,6}

Geological features of Larderello-Travale and Mt. Amiata geothermal areas (southern Tuscany, Italy)

¹ Enel GreenPower S.p.a. Via Andrea Pisano, 120 - Pisa (Italy); batini.fausto@enel.it

² Department of Earth Sciences, University of Siena - Via Laterina, 8 - Siena (Italy); brogiandrea@unisi.it

³ Department of Earth Sciences, University of Siena - Via Laterina, 8 - Siena (Italy); lazzarotto@unisi.it

⁴ Department of Geology and Geophysics, University of Bari - Via Orabona 4 - Bari (Italy); d.liotta@geo.uniba.it

⁵ Department of Earth Sciences, University of Florence - Via G. La Pira, 4 - Firenze (Italy); pandeli@geo.unifi.it

⁶ CNR-Institute of Earth Sciences and Earth Resources-Section of Florence, Via G. La Pira, 4 - Firenze (Italy).

This paper summarises the geological features of the Larderello-Travale and Monte Amiata areas, where the world's most ancient exploited geothermal fields are located. In both geothermal areas, three regional tectonostratigraphic elements are distinguished, from the top: (a) Late Miocene-Pliocene and Quaternary, continental to marine sediments; (b) the Ligurian and Sub-Ligurian complexes, which include remnants of the Jurassic oceanic realm and of the transitional area to the Adriatic margin, respectively; (c) the Tuscan Unit (Tuscan Nappe), composed of sedimentary rocks ranging in age from Late Triassic to Early Miocene. The substratum of the Larderello and Monte Amiata areas is referred to as the Tuscan Metamorphic Complex. This is mainly known through drilling of geothermal wells. This complex is composed of two metamorphic units: the upper Monticiano-Roccastrada Unit and the lower Gneiss Complex. The Monticiano-Roccastrada Unit consists of (from top to bottom): the Verrucano Group, the Phyllite-Quartzite Group and the Micaschist Group. The Gneiss Complex consists only of pre-Alpine polymetamorphic gneiss. The Tuscan Metamorphic Complex is affected by contact metamorphism by Plio-Quaternary granitoids and their dyke swarms. Hydrothermal phenomena still occur in both geothermal fields. The Larderello-Travale and Mt. Amiata geothermal fields are located in the inner Northern Apennines, in an area that has been subject to extension since the ?Early-Middle Miocene. Two main extensional events are well expressed in the structures of the geothermal areas. The first extensional event (?Early-Middle Miocene) determined the tectonic delamination of the Ligurian Units and Tuscan Nappe. The second extensional event (Late Miocene–Present) is characterized by high-angle normal faults bounding the Neogene tectonic depressions of southern Tuscany.

Introduction

Continental extensional tectonic environments with high heat flow are often affected by geothermal systems, independently from the geodynamic context in which they are located (Barbier, 2002 and references therein). Extension also characterises southern Tuscany (inner Northern Apennines), where the most important geothermal fields of Italy are located (Figure 1).

The structural and stratigraphic setting of southern Tuscany derives from two different deformational processes: the first one is linked to the convergence between the European margin and the Adria microplate (Cretaceous–Early Miocene), producing the stacking of the Northern Apennines nappes; the second is related to the post-collisional extensional tectonics which have affected the inner zone of the Northern Apennines since the Early–Middle Miocene (Carmignani et al., 1994; Brunét et al., 2000 and references therein). This latter process is reflected by: (a) the present crustal and lithospheric thicknesses of about 22 km and 30 km respectively

Figure 1 Structural sketch map of southern Tuscany with the regional heat flow contour lines (equidistance: 50 mW/m²). The Larderello-Travale and Mt. Amiata geothermal fields are located in areas where heat flow reaches 1 W/m² and 0.6 W/m², respectively. (after Baldi et al., 1995)

Figure 2 The Larderello Valley ("Devil's Valley") in a 19th century print.

(Calcagnile and Panza, 1981); (b) the high heat flow (Baldi et al., 1995) that characterises southern Tuscany (120 mW/m^2 on average, with local peaks up to 1000 mW/m^2); (c) the anatectic to subcrustal magmatism that has affected southern Tuscany during the Late Miocene to Pleistocene time period (Serri et al., 1993). The Tuscan magmatism is coupled with Pliocene-Quaternary hydrothermal mineralization and widespread geothermal vents.

This paper summarises the geological features of the Larderello-Travale and Mt. Amiata geothermal areas, the most ancient exploited geothermal fields in the world. Particularly, the Larderello field has been industrially exploited since 1818 (Figure 2), when the Montecerboli Count, Francesco de Larderel, extracted boric acid from the geothermal vents. In 1904, the Larderello geothermal fluids were used to produce electricity by Prince Piero Ginori Conti. In contrast, the Mt. Amiata area has been exploited since the early 1960s, when the first electrical power plant was activated.

Today the endogenous fluids, intercepted at depth by boreholes, feed the Larderello-Travale and Mt. Amiata power plants belonging to the Enel GreenPower Electric Company. Present production is more than 700 MW, corresponding to about 2% of the total electricity production in Italy (Cappetti et al., 2000).

Geological features of the Larderello-Travale and Monte Amiata areas

The geological evolution of the Northern Apennines is well expressed in the structure of the Larderello-Travale and Monte Amiata geothermal fields.

Larderello-Travale Area

In the Larderello-Travale area three regional tectonostratigraphic elements crop out (Figure 3). These are, from top to bottom:

- (1) Neogene and Quaternary deposits: Late Miocene to Pliocene and Quaternary, continental to marine sediments, filling up the extensional tectonic depressions which, in the geothermal areas, unconformably overlie the pre-Neogene substratum (Figure 4).
- (2) The Ligurian Complex l.s.. This includes the Ligurian units s.s. and the Sub-Ligurian Unit. The Ligurian units are composed of remnants of the Jurassic oceanic basement and its pelagic sedimentary cover. The Sub-Ligurian Unit ("Argille e calcari" Unit) belongs to a palaeogeographical domain interposed between the Ligurian Domain and the Tuscan Domain (Figure 5). The Ligurian

Figure 3 Geological sketch map of the Larderello-Travale area. Key: Neogene and Quaternary deposits: 1—Quaternary continental sediments; 2—Pliocene marine sediments; 3—Miocene continental and marine sediments; 4—Ligurian units l.s. (Jurassic-Eocene); 5—Tuscan Nappe: Late Triassic-Early Miocene sedimentary sequence; 6—Tuscan Nappe: Late Triassic basal evaporite (Burano Fm.); 7—Palaeozoic Phyllite-Quartzite Group (MRU₂) and Triassic Verrucano Group (MRU₃); 8—Normal faults; 9—Main geothermal fields; 10—Trace of geological cross-section. (MRU₁)—Palaeozoic Micaschist Group; (GC)—Gneiss Complex.

Figure 4 Stratigraphic relationships among the Neogene formations cropping out in the surroundings of the Larderello-Travale geothermal area; RAQ: Raques Stream Fm. (Early Messinian), ROS: Rosignano Limestone (Early Messinian), EMO: Clays and gypsum of Era Morta River (Late Turolian), BAM: Montebamboli Conglomerate (Late Turolian); AZR: Blue Clays (Late-Middle Pliocene); VLM: Villamagna Fm. (Middle Pliocene).

Figure 5 a) Structural and stratigraphic relationships between the Ligurian and Subligurian Units in the Larderello-Travale and Mt. Amiata geothermal areas. Ophiolitic Unit: Σ , Γ : Ophiolites (serpentinites, gabbros, basalts—Middle-Late Jurassic), gc_1 : Mt. Alpe cherts (Late Jurassic), c_1 : Calpionella limestone (Early Cretaceous), c_2 : Palombini shales (Early Cretaceous); Monteverdi-Lanciaia Unit: MTV: Monteverdi Marittimo Fm. (Cretaceous-Early Palaeocene), LF: Lanciaia Fm. (Early-Middle Eocene); S. Fiora Unit: SFF: Santa Fiora Fm. (Late Cretaceous), PF: Pietraforte Fm. (Late Cretaceous), MMF: Monte Morello Fm. (Paleocene-Eocene); Subligurian Unit: CF: Canetolo Fm. (Paleocene-Eocene).
b) Reconstructed relationships among the Ligurian, Subligurian Units and Tuscan Nappe at the end of the collisional stage (Late Oligocene-Early Miocene).

I.s. Complex was thrust eastwards over the Tuscan Domain during latest Oligocene to Early Miocene times.

- (3) The Tuscan Unit (Tuscan nappe). This is related to part of the Late Triassic-Early Miocene sedimentary cover of the Adria continental palaeomargin (Figure 6). The Tuscan Nappe was detached from its substratum along the Triassic evaporite level and was thrust over the outer palaeogeographical domains during the Late Oligocene-Early Miocene compression.

The substratum of the Larderello-Travale area is referred to as the Tuscan Metamorphic Complex. This is mainly known through drillings of the geothermal fields, some of these penetrating down to about 4.5 km. This Complex is composed of two metamorphic units (Bertini et al., 1994): the upper Monticiano-Roccastrada Unit and the lower Gneiss Complex.

The Monticiano-Roccastrada Unit consists of three groups (Figure 7):

- The Verrucano Group. This is made up of Carnian phyllites and metacarbonates, related to marine littoral facies, and Middle-Early Triassic continental quartzites and quartz conglomerates. The Verrucano Group is imbricated in duplex structures, often separated by Late Triassic evaporites and Early-Late Palaeozoic phyllites and quartzites.

Figure 6 Stratigraphic succession of the Tuscan Nappe.

Symbols: O: Macigno Fm. (Late Oligocene-Early Miocene); ce: Scaglia toscana Fm. (Cretaceous-Oligocene); c^1 : Maiolica Fm. (Early Cretaceous); g^3 : Diaspri Fm. (Malm); g^{2m} : Marne a Posidonia (Dogger); g^{2s} : Calcare Selcifero Fm. (Middle-Late Liassic); g^2 : Calcare Rosso ammonitico (Early-Middle Liassic); g^1 : Calcare Massiccio (Early Liassic); t^2 : Calcare a Rhaeticula contorta (Rhaetic); t^1 : Burano Fm. and Calcare cavernoso (Noric-Rhaetic).

- The Phyllite-Quartzite Group. This mainly consists of Palaeozoic phyllite and quartzite, affected by the Alpine greenschist metamorphism which overprints a previous Hercynian blastesis. Layers of anhydritic dolomites and basic metavolcanites in lenses can occur.
- Micaschist Group. This includes Palaeozoic rocks (garnet-bearing micaschists and quartzites with amphibolite zones) affected by Alpine and Hercynian deformations. Particularly, the micaschists were affected by a synkinematic Hercynian metamorphism and by an Early Permian thermal event (Del Moro et al., 1982; Pandeli et al., 1994 and references therein).

The Gneiss Complex consists of pre-Alpine polymetamorphic gneiss and paragneiss with intercalations of amphibolites and orthogneiss. In contrast to the Monticiano-Roccastrada Unit, the effects of the Alpine orogeny are not recorded in the Gneiss Complex (Elter and Pandeli, 1990). At different depths, deep boreholes encountered granitoids and felsic dykes (3.8–2.25 Ma, Villa & Puxeddu, 1994; Gianelli and Laurenzi, 2001) whose emplacement

Figure 7 Tectonostratigraphic units in the Larderello-Travale and Mt. Amiata areas. Q-P-M: Quaternary, Pliocene and Miocene sediments; MR—Magmatic rocks; Tuscan Nappe (TN): TN_2 —Early Miocene-Rhaetic sequence; TN_1 —Late Triassic evaporite (Burano Fm.); Monticiano-Roccastrada Unit (MRU): MRU_3 —Triassic Verrucano Group; MRU_2 —Palaeozoic Phyllite-Quartzite Group; MRU_1 —Palaeozoic Micaschist Group; GC: Palaeozoic Gneiss Complex.

gave rise to contact aureoles in the metamorphic host rocks (Elter and Pandeli, 1990; Musumeci et al., 2002 and references therein). Moreover, hydrothermal mineral associations (Gianelli, 1994), locally no older than 270,000 years and no younger than 10,000 years (Bertini et al., 1996), partially or totally fill the fractures affecting the Larderello metamorphic rocks.

Mt. Amiata Area

The geological framework of Mt. Amiata (Figure 8) is characterised by the trachitic-latitic Mt. Amiata volcano (0.3–0.2 Ma; Ferrari et al., 1996 and references therein). The outcropping units belong to the already mentioned Ligurian and Sub-Ligurian units (Figure 5) and to the Tuscan Nappe (Figure 6). The Monticiano-Roccastrada Unit does not crop out in the Mt. Amiata area, but it has been encountered by geothermal wells (Figure 9). This Unit is made up of very low-grade metamorphic sequences (Elter & Pandeli, 1991 with references therein) with: (a) Triassic Verrucano Group (MRU3 in Figure 7); (b) graphitic phyllite and metasandstone of probable Carboniferous age (Formation a); (c) ?Devonian hematite-rich and anhydrite-bearing chlorite phyllite, metasandstone with dolostone levels (Formation b); (d) Late Permian fusulinid-bearing crystalline limestone and dolostone with intercalations of graphitic phyllite (Formation c) (MRU2* in Figure 7).

Relicts of micaschists and gneisses have been discovered as xenoliths in the Mt. Amiata lavas (Van Bergen, 1983) (MRU1-GC in Figure 7), suggesting their occurrence at depth. Also the metamorphic rocks of the Mt. Amiata geothermal area are affected by the thermometamorphism and hydrothermalism linked to the recent magmatism (Gianelli et al., 1988).

Figure 8 Geological sketch map of the Mt. Amiata area. **Keys:** 1—Quaternary continental sediments; 2—Magmatic rocks; 3—Pliocene marine sediments; 4—Miocene continental, brackish and marine sediments; 5—Ligurian Units l.s. (Jurassic-Eocene); 6—Tuscan Nappe (Late Trias-Early Miocene); 7—normal faults; 8—Main geothermal fields; 9—Trace of the geological cross-section; (TN₁)—Tuscan Nappe: Late Triassic basal evaporite (Burano Fm.); (MRU₃)—Triassic Verrucano Group; (MRU₂*)—Palaeozoic phyllite Group (stratigraphic details are shown in Figure 9).

Figure 9 Relationship among the Triassic and Palaeozoic formations belonging to Monticiano-Roccastrada Unit encountered by geothermal wells in the Mt. Amiata area (after Elter & Pandeli, 1991).

Extensional structural features

Two different extensional events affected southern Tuscany after the emplacement of the Northern Apennines units. These are well expressed in the structures of the Larderello-Travale and Mt. Amiata geothermal areas (Figures 3 and 8). The first extensional event produced low-angle normal faults which soled out in the Late Triassic evaporites or in the Palaeozoic phyllites. According to some authors (Baldi et al., 1994; Carmignani et al., 1994) this first extensional event is related to ?Early-Middle Miocene on the basis of both stratigraphic considerations and mineral cooling ages linked to the exhumation of the Alpi Apuane core complex (Kligfield et al., 1986). The second extensional event (Late Miocene-Present) is characterized by high-angle normal faults which dissected all the previous structures and defined the Neogene tectonic depressions.

Reflection seismic features

Information on deeper structures derives from seismic reflection surveys carried out by Enel S.p.a. for geothermal exploration in the Larderello-Travale and Mt. Amiata areas. The seismic sections show a poorly reflective upper and a highly reflective mid-lower crust, particularly in the Larderello-Travale area (Cameli et al., 1993; Brogi et al., 2003). The top of the reflective crust is marked by a rather continuous reflector of high amplitude and frequency called the K-horizon (Batini et al., 1978), which locally exhibits bright spot features (Batini et al., 1985). The K-horizon ranges in depth from 3 to 8 km (Cameli et al., 1998 and references therein) both in the Larderello-Travale and Mt. Amiata fields (Figures 10 and 11). Present-Pliocene normal faults tend to flatten at the K-horizon depth or just below it (Cameli et al., 1993). 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 (Liotta and Ranalli, 1999 and references therein). Gianelli et al. (1997) hypothesised that a granite carapace and associated wall rocks, probably delimited by overpressurised horizons, could give rise to the K-reflector. Furthermore, temperature data, hypocentral distributions and rheological predictions led to the explanation of the K-horizon as the top of an active shear zone, located at the brittle/ductile transition (Cameli et al., 1993; 1998; Liotta & Ranalli, 1999). In this framework,

Figure 10 Contour lines in kilometres (equidistance: 0.5 km) of the K-horizon depth. A and B show respectively the Larderello-Travale and Mt. Amiata geothermal areas (after Cameli et al., 1998).

Figure 11 The K-horizon in the Larderello-Travale geothermal area. Vertical axis: TWT seconds.

the K-horizon would not represent a lithological boundary, even if it locally coincides with the roof of a magmatic body.

Geothermal reservoirs and fluids

Both in the Larderello-Travale and Mt. Amiata fields, there are two geothermal reservoirs recognised and industrially exploited (Cappetti et al., 2000; Bertini et al., 1995): one more superficial, located in the cataclastic horizon corresponding to the Late Triassic evaporites and the overlying Jurassic carbonatic formations; and a deeper one, located in fractured metamorphic rocks at depths ranging between 2000 and 4500 m. The Cretaceous–Early Miocene terrigenous formations of the Tuscan Nappe, the Ligurian Units l.s. and the Miocene-Pliocene sediments represent the impervious cover of the more superficial geothermal reservoir.

The geothermal fluids are mainly made up of a mixture of meteoric water with thermometamorphic and magmatic fluids (Minissale, 1991; Manzella et al., 1998).

The Larderello-Travale geothermal field produces high enthalpy geothermal fluids ($T = 150^{\circ}\text{--}260^{\circ}\text{C}$; $P = 2\text{--}15$ bar) which mainly comprise superheated steam and minor gases (max 15% by weight) essentially made up of CO_2 and H_2S . The average flow rate of the wells is 25 t/h of dry steam (max 350 t/h). In the deeper reservoir, pressure and temperature increase with depth, up to values of 70 bar and 350°C .

The Monte Amiata geothermal area has two water-dominated fields (Bagnore and Piancastagnaio fields). In the deeper reservoir, $P = 200\text{--}250$ bars and $T = 300^{\circ}\text{--}360^{\circ}\text{C}$. The resulting fluids are two-phase mixtures with $T = 130^{\circ}\text{--}190^{\circ}\text{C}$ and $P = 20$ bars. Fluids are

characterised by a TDS content of about 10–12 g/l (mainly alkaline chlorides and, to a lesser extent, alkaline earth bicarbonates) and a gas percentage similar to that of the Larderello field.

Concluding remarks

Field information integrated with borehole and seismic data allow the reconstruction of the structural and stratigraphic features of the Larderello-Travale and Mt. Amiata geothermal areas. We emphasise two main points:

- These geothermal areas are located in a regional extensional context whose development favoured the localization of fractured zones, magmatism and high heat flow.
- Deep fractured zones in the metamorphic rocks and cataclasites in the Triassic evaporite levels represent the reservoirs in both described geothermal areas. In principle, in geothermal areas the permeability is time-dependent, since the circulation of geothermal fluids favours the deposition of hydrothermal minerals. However, fractures are maintained open only if microseismicity occurs, as is the case in both geothermal areas (Cameli et al., 1993; 1998).

References

- Baldi P., Bellani, S., Ceccarelli, A., Fiordelisi, A., Squarci, P. and Taffi, L., 1995, Geothermal anomalies and structural features of southern Tuscany - World Geothermal Congress Proceedings - Florence, Italy, May 1995, 1287-1291.
- Baldi, P., Bertini, G., Cameli, G.M., Decandia, F.A., Dini, I., Lazzarotto, A. and Liotta D., 1994, La tettonica distensiva post-collisionale nell'Area Geotermica di Larderello (Toscana meridionale), *Studi Geol. Camerti*, Vol. spec., 1994/1, 183-193.
- Barbier, E., 2002, Geothermal energy and current status: an overview, *Renewable and sustainable energy, Reviews*, 6, 3-65.
- Batini, F., Burgassi, P. D., Cameli, G. M., Nicolich, R. and Squarci P., 1978, Contribution to the study of the deep lithospheric profiles: deep reflecting horizons in Larderello-Travale geothermal field, *Mem. Soc. Geol. It.*, 19, 477-484.
- Batini, F., Bertini, G., Gianelli, G., Pandeli, E. and Puxeddu M., 1985, Deep structure of the Larderello field: contribution from recent geophysical and geological data, *Mem. Soc. Geol. Ital.*, 25 (1983), 219-235.
- Bertini, G., Cameli, G.M., Costantini, A., Decandia, F.A., Dini, I., Elter, F.M., Lazzarotto, A., Liotta, D., Pandeli, E. and Sandrelli, F., 1994, Structural features of southern Tuscany along the Monti di Campiglia-Rapolano Terme cross-section, *Mem. Soc. Geol. It.*, 48, 51-59.
- Bertini, G., Cappetti, G., Dini, I. and Lovari, F., 1995, Deep drilling results and updating of geothermal knowledge of the Monte Amiata area, *Proceedings of the World Geothermal Congress, Florence (Italy) 18-31 May 1995 - International Geothermal Association (1995)*, 2, 1283-1286.
- Bertini, G., Gianelli, G. and Battaglia, A., 1996, Risultati ed interpretazione delle datazioni radiometriche (metodo $^{230}\text{Th}/^{234}\text{U}$) dei campioni di minerali idrotermali presenti nelle rocce attraversate dai sondaggi geotermici (Larderello e Monteverdi) e negli affioramenti di rocce mineralizzate (Sassa e Canneto-Malentrata), *ENEL-CNR-CISE internal report*, Pisa 1996, 18 pp.
- Brogi, A., Lazzarotto, A., Liotta, D. and Ranalli G., 2003, Extensional shear zone as imaged by reflection seismic lines: the Larderello geothermal field (central Italy), *Tectonophysics*, 363, 127-139.
- Brunet, C., Monié, P., Jolivet, L. and Cadet, J.P., 2000, Migration of compression and extension in the Tyrrhenian Sea, insights from $^{40}\text{Ar}/^{39}\text{Ar}$ ages on micas along a transect from Corsica to Tuscany, *Tectonophysics*, 321, 127-155.
- Calcagnile, G., and Panza, G.F., 1981, The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions, *Pure Appl. Geophys.*, 119, 865-879.
- Cameli, G.M., Dini, I. and Liotta, D., 1993, Upper crustal structure of the Larderello geothermal field as a feature of post collisional extensional tectonics (Southern Tuscany, Italy), *Tectonophysics*, 224, 413-423.
- Cameli, G.M., Dini, I. and Liotta, D., 1998, Brittle/ductile boundary from seismic reflection lines of southern Tuscany (Northern Apennines, Italy), *Mem. Soc. Geol. It.*, 52, 153-163.
- Cappetti, G., Passaleva, G., Sabatelli, F., 2000, Italy country update report 1995-1999, *Proc. World Geother. Congr. 2000, Kyushu-Tohoku, May 28-June 10*, 109-116.

- Carmignani L., Decandia F.A., Fantozzi P.L., Lazzarotto A., Liotta D. and Meccheri M., 1994, Tertiary extensional tectonics in Tuscany (Northern Apennines, Italy), *Tectonophysics*, 238, 295-315.
- Del Moro, A., Puxeddu, M., Radicati Di Brozolo, F., and Villa, I. M., 1982, Rb-Sr & K-Ar ages on minerals at temperatures of 300-400°C from deep wells in the Larderello geothermal field (Italy), *Contr. Mineral. Petrol.*, 81, 340-349.
- Elter, F.M. and Pandeli, E., 1990, Alpine and Hercynian Orogenic phases in the Basement rocks of the Northern Apennines (Larderello Geothermal field, Southern Tuscany, Italy), *Ecl. Geol. Elv.*, 83(2), 241-264.
- Elter, F.M. and Pandeli, E., 1991, Structural features of the metamorphic Palaeozoic - Triassic sequences in deep geothermal drillings in the Monte Amiata area (SE Tuscany, Italy), *Boll. Soc. Geol. Ital.*, 110, 511-522.
- Ferrari, L., Conticelli, S., Burlamacchi, L. and Manetti, P., 1996, Volcanological evolution of the Monte Amiata, Southern Tuscany: New geological and petrochemical data, *Acta Vulcanologica*, 8, 41-56.
- Gianelli, G., 1994, Ipotesi di un modello di crosta superiore per le aree geotermiche toscane, *Studi Geologici Camerti*, Vol. Spec. 1994/1, CROP18, 195-200.
- Gianelli, G., and Laurenzi, M.A., 2001, Age and cooling rate of the geothermal system of Larderello, *Geoth. Resources Council Transaction*, 25, 731-735.
- Gianelli, G., Manzella, A. and Puxeddu, M., 1997, Crustal models of the geothermal areas of southern Tuscany, *Tectonophysics*, 281, 221-239.
- Gianelli, G., Puxeddu, M., Batini, F., Bertini, G., Dini, I., Pandeli, E. and Nicolich, R., 1988, Geological model of a young volcano-plutonic system: the geothermal region of Monte Amiata (Tuscany, Italy), *Geothermics*, 17, 719-734.
- Kligfield, R., Hunziker, J., Dallmeyer, R.D. and Schamel, S., 1986, Dating of deformation phase using K-Ar and ^{40}Ar - ^{39}Ar techniques: Results from the Northern Apennines, *Jour. of Structural Geol.*, 8, 781-798.
- Liotta, D. and Ranalli, G., 1999, Correlation between seismic reflectivity and rheology in extended lithosphere: southern Tuscany, Inner Northern Apennines, Italy, *Tectonophysics*, 315, 109-122.
- Manzella, A., Ruggieri, G., Gianelli, G. and Puxeddu, M., 1998, Plutonic-geothermal system of southern Tuscany: a review of the crustal models, *Mem. Soc. Geol. It.*, 52, 283-294.
- Minissale, A., 1991, The Larderello geothermal field: a review, *Earth-Sciences Reviews*, 31, 133-151.
- Musumeci, G., Bocini, L. and Corsi, R., 2002, Alpine tectonothermal evolution of the Tuscan Metamorphic Complex in the Larderello geothermal field (Northern Apennines, Italy), *Jour. of the Geol. Soc., London*, 159, 443-456.
- Pandeli, E., Gianelli, G., Puxeddu, M. and Elter, F.M., 1994, The Paleozoic basement of the Northern Apennines: stratigraphy, tectono-metamorphic evolution and Alpine hydrothermal processes, *Mem. Soc. Geol. It.*, 48, 627-654.
- Serri, G., Innocenti, F. and Manetti, P., 1993, Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of Central Italy, *Tectonophysics*, 223, 117-147.
- Van Bergen, M.J., 1983, Polyphase metamorphic sedimentary xenoliths from Mt. Amiata volcanics (Central Italy): evidence for a partially disrupted contact aureole, *Geol. Rundsch.*, 72, 637-662.
- Villa, I. and Puxeddu, M., 1994, Geochronology of the Larderello geothermal field: new data and the 'closure temperature' issue, *Contrib. Mineral. Petrol.*, 315, 415-426.

Fausto Batini is manager of geothermal exploration of the Enel Green Power Italian electric company. He has published numerous research papers on the Italian geothermal fields.

Andrea Brogi is Post-Doctoral fellowship at the Department of Earth Science of Siena University, Italy. His research interest is focused on tectonic evolution of the Northern Apennines and, in particular, on the extensional tectonics affecting the Tyrrhenian Sea and Tuscany.

Antonio Lazzarotto is Full Professor of Geology at the Department of Earth Science of Siena University, Italy. He is author of stratigraphic papers, geological surveys and geological syntheses about the Northern Apennines. He was Leader of several national and multidisciplinary projects (Progetto Energetica, CROP, New Edition of the Geological Map of Italy).

Domenico Liotta is Associate Professor of Structural Geology at the Geology and Geophysics Department of Bari University, Italy. He is author of several papers on the evolution and structure of the Larderello crust.

Enrico Pandeli is Associate Professor of Stratigraphy and Sedimentary Geology at the Earth Science Department of Florence University, Italy. His scientific interests mainly regard the stratigraphy, petrography and structural setting of the metamorphic and sedimentary tectonic Units of the Northern Apennines.