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# Characteristics of Geothermal Fields in Italy

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ABSTRACT. The main Italian geothermal fields are located in the Tyrrhenian pre-Apennine belt. With the exception of Larderello, all the others fields are in correspondence of volcanic areas. The geothermal exploration started in Tuscany at the beginning of the last century. Both in Larderello and Mt. Amiata the geothermal reservoir is hosted by mesozoic carbonatic formations and by the metamorphic basement, with temperatures of 200 – 350° at depth of 500 – 3500 m. The geothermal resource of Larderello consists of superheated steam wile the Mt. Amiata system is steam – water dominated. In the middle of 70's geothermal exploration was extended to Latium, Campanian and Sicily regions. All the discovered reservoirs are water dominated with high salinity. Unfavourable characteristics of these reservoirs and environmental problems discouraged the exploitation of these fields. At present only the areas of Larderello, Travale-Radicondoli and Mt. Amiata are on exploitation. In the year 2004 the electricity generation reached the maximum historical value of 5437 GWh gross.

*Key terms:* Exploration and exploitation, Geothermal resources, Reservoir, Energy production

## Introduction

The exploration and exploitation of high-temperature geothermal resources for electricity production started in Italy at the beginning of the last century in the Larderello and Travale areas (Tuscany). In the second half of the last century, these activities were then extended to several other areas of potential interest, all of them located in the Tyrrhenian pre-Apennine belt of central-southern Italy and in the Aeolian Islands (Fig. 1

An exploration program was carried out, with the integration of many surface surveys, both in Tuscany and in Latium regions. Geological, geophysical and geochemical surveys, as well as drilling activities, were performed in the main Tuscan geothermal fields (Larderello, Travale and Mt. Amiata) and in their surrounding areas.

In the Latium region, these exploration activities were performed in Joint Venture by Enel and Agip in many areas North of Rome (Latera caldera, Vico Lake, Cesano, Bracciano Lake) and South of Rome (Alban Hills). In all these areas about 100 deep wells were drilled. In the Roccamonfina area (South of Rome) a single well was drilled by Unocal (USA). Also in southern Italy, geothermal exploration was performed by Enel–Agip Joint Venture in Campania, the Phlegraean fields and Ischia island, and in the islands of Sicily, Vulcano and Pantelleria (BUONASORTE *et alii*, 1995). Unfavorable characteristics of the potential reservoirs (poor permeability, aggressive fluid, etc.), together with others logistical or environmental problems (urbanization, tourist nature of zones, etc.), hindered geothermal development in many of these areas.

Indirect uses of the geothermal fluids (heating, green house, aquaculture etc.) were carried out in the above-mentioned geothermal fields and in other low enthalpy geothermal areas. One of these is the Po valley (North of Italy, see Fig. 1) where geothermal direct uses have been

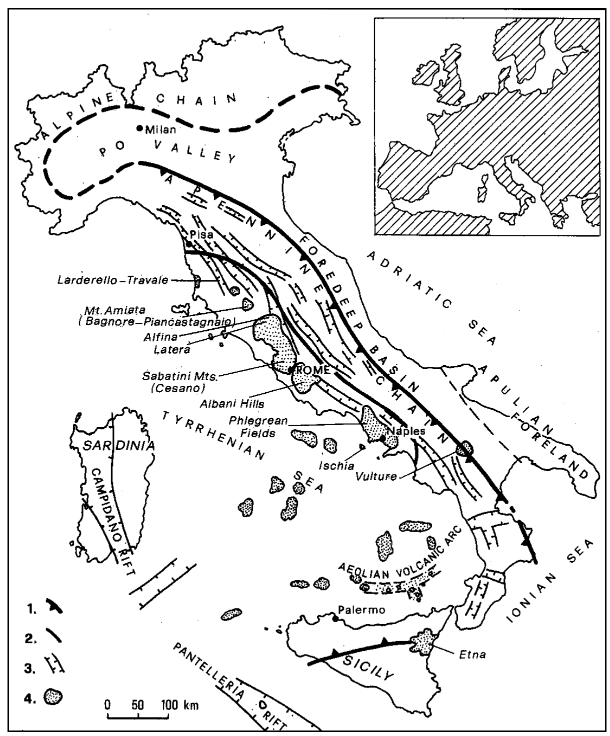



FIG.1. Structural skectch map of Italy with location of main geothermal areas. 1) Thrust front of the Apennine chain. 2) Approxmative mainland of crustal thinning. 3) Main recent tensional structures. 4) Main recent volcanic areas

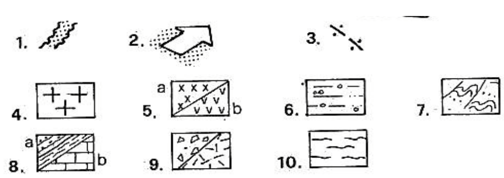
applied to a heating project for the city of Ferrara. This project was carried out using hot water coming from wells drilled for oil exploration (Agip).

## Main geological data of central Italy

During the 1990s, more than 800 geothermal wells were drilled mainly in the southern part of Tuscany and northern part of Latium allowing much geothermal information to be acquired at greater depths. The average depth of the wells was about 2000 m, and in some cases over 4000 m.

The western-central Italian belt belonging to the Tyrrhenian-Apennine orogenic system (Eocene-Quaternary age) can be considered a "compressional fold thrust belt " (CARMIGNANI & KLIGFIELD, 1990). This geological structure is constituted by a series of overthrust nappes with a prevalently north-eastward or eastward vergence (Fig. 2).

In Tuscany the deepest drillings explored a Complex of Gneiss in the "Amphibolite Facìes" (Lower Paleozoic to Precambrian) of medium to high metamorphic grade. Also constituted by a series of overthrust nappes with a prevalently north-eastward or eastward vergence, this Complex is not substantially deformed by Alpine orogeny and can be considered the "autochthonous" regional basement (BERTINI *et alii*, 1991).




LEGEND:
1) Transgression surface;
2) Overthrust surface;
3) Thermometamorphic aureola;
4) Magmatic body;
5) Rhyodacites (Tuscan prov.);
6) K- alkaline volcanites (Roman comagmatic prov.);
7) Ligurids;
8) Tuscan Nappe, a: terrigenous form. b: carbonatic form;
9) Tectonic Wedges complex;
10) Paleozoic metamorphic" Basement"

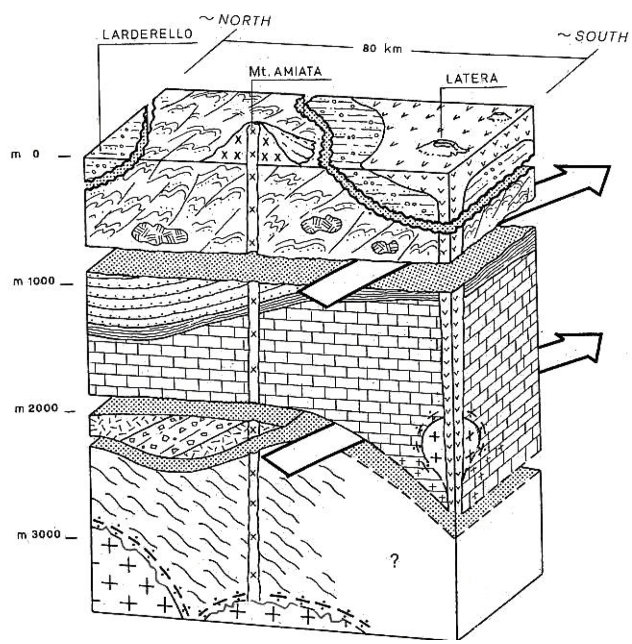



FIG. 2: Block diagram showing the structural setting of the Tuscan – Latium geothermal areas (Battaglia et al. 1991).

The overlying unit is an overthrust nappe, named Monticiano – Roccastrada Unit (BERTINI *et alii*, 1991) that overthrust from west to east during the Alpine orogeny (Tortonian). It is separated from the basement by a mylonitic horizon linked to this orogenic phase (ELTER & PANDELI, 1990). This unit is made up of metamorphic Paleozoic formations (micaschists, phyllites, etc.) and of quartzitic, evaporitic and carbonate formations (Trias – Paleozoic) which were affected by the Alpine deformation and constitute the Tectonic Wedges complex (PANDELI *et alii*, 1991). Outcroppings of the metamorphic units are found only in Tuscany and North of Latium, but outside Tuscany, no geothermal drillings have ever been performed in these formations.

The sedimentary Tuscan Nappe overthrusts the metamorphic ones. It is made up of a mainly carbonate sequence (Upper Trias) at the base and prevalently terrigenous (Lower Miocene) one at the top. The Tuscan Nappe is also characterized by "extensional tectonic processes" which locally determined the direct superposition of the "Ligurid" Units both on its oldest formations and on the metamorphic ones. The Ligurid Units (Eocene - Lower Cretaceous) are mainly made up of shales, limestones, marly limestones and sandstones. Locally they embed ophiolitic bodies.

In northern Latium the deepest drilled geologic levels are the dolomitic–anhydrite Triassic formations of the Tuscan Nappe l.s.(BUONASORTE *et alii*, 1991). In both southern-central Tuscany and northern Latium, the tensional tectonics phase, occurring from Lower Miocene to Quaternary age, formed many sedimentary basins which are mainly elongated in a NW-SE direction and are filled by Neoautochthonous sediments (clay, conglomerates and sands). To complete the regional stratigraphic-structural framework of the Tuscan-Latium region, the magmatic phenomena, that affected the Tyrrhenian belt of central Italy from the Upper Miocene to the Recent Quaternary age, have been followed by geothermal implications.

Magmatic rocks outcrop discontinuously in southern-central Tuscany (see Fig. 1) and much more extensively in northern Latium. The magmatic and volcanic manifestations are gradually younger going from west to east, according to the migration of the tensional phase (BORSI *et alii*, 1967; MARINELLI, 1961; CIVETTA *et alii*, 1978). The Tuscan igneous rocks, both intrusive and effusive, and the oldest Latiun ones, are chiefly of the acid type, oversaturated in silica, and transitional subalkalíne s.l.. They form the so-called "Tuscan Magmatic Province". The most recent Latiun Volcanites (from Latera to the Alban Hills areas) are alkaline-potassic and undersaturated in silica, and belong to the "Roman Comagmatic Province" (BARBERI *et alii*, 1971; LOCARDI, 1986; LA VECCHIA & STOPPA, 1989; MARINELLI, 1961; WASHINGTON, 1906).

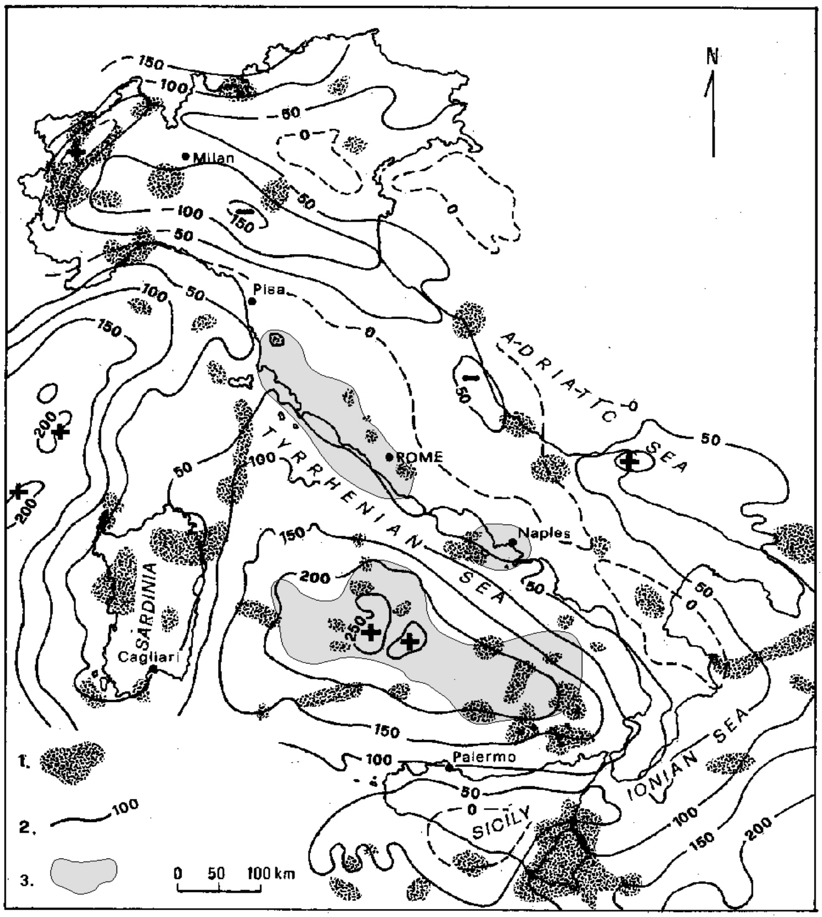



FIG.3: Skecth map of the main gravimetric, magnetic and heath flow data (C.N.R. 1975; Cassano et al., 1986). 1) Magnetic high. 2) Bouguer countour line (mgal). 3) Heath flow high

On the basis of the geological and geophysical data, the central part of the Italian peninsula can be subdivided into the following structural belts:

- a western belt which is characterized by the contemporaneous presence of structural highs of the metamorphic basement, recent tensional basins and magmatic and volcanic manifestations;
- a central belt which corresponds to the Apennines s.s. chain and is characterized by a considerable thickness of the sedimentary formation;
- an eastern belt which is constituted by the sedimentary basin of the Adriatic foreland.

These structural features are in agreement with regional gravimetric, heat flow and magnetic anomalies (Fig. 3) as follows:

- gravity anomalies are mainly oriented NW-SE, and a wide positive anomaly, centered on the Tyrrhenian Sea, extends its effect along all the Tyrrhenian coast of Italy;
- heat flow highs (> 150 $MW/m^2$) are present along the western coast of Italy, from Pisa to Naples, and in the central part of the Tyrrhenian Sea (DELLA VEDOVA *et alii* , 1991; MONGELLI *et alii*, 1991);
- a series of positive and high-frequency magnetic anomalies are mainly present in the Tyrrhenian Sea in

correspondence with volcanic areas.

All these geophysical features can be correlated to a considerable thinning of the lithosphere (< 25 km; Panza et al., 1980) which characterizes the Tyrrhenian Sea and the Tuscan–Campania coastal belts.

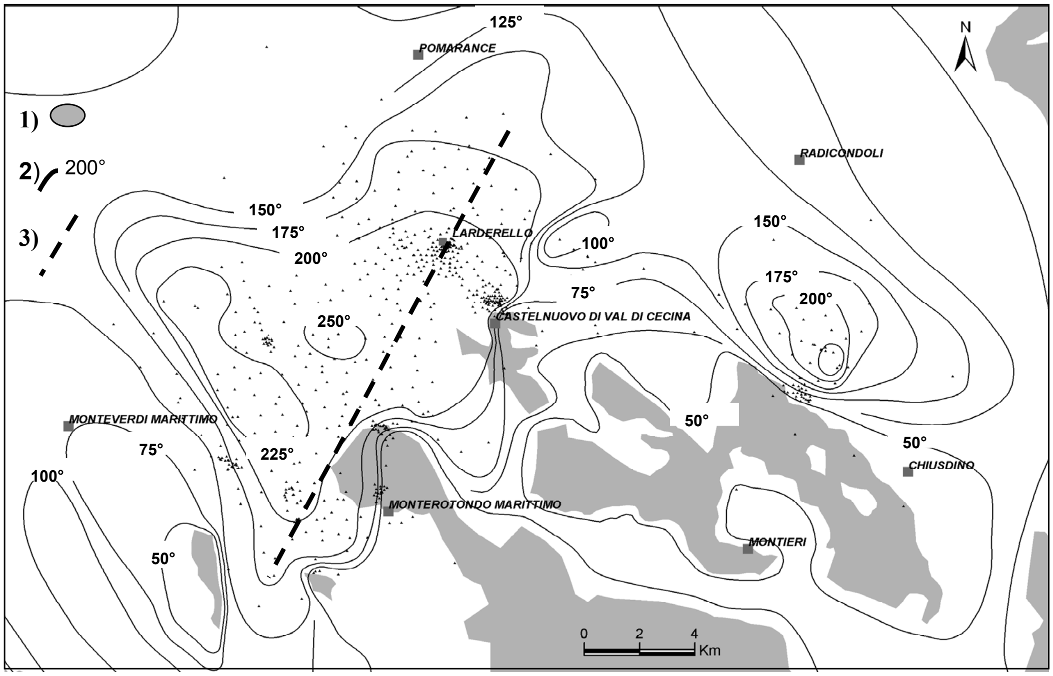



FIG.4: Temperature distribution at the carbonate reservoir top in the Larderello – Travale geothermal field. LEGEND: 1) Outcrops of the carbonate – evaporitic formation of the TUSCAN NAPPE (shallower geothermal reservoir) 2) Temperature distribution at the shallower geotermal reservoir top. 3) Trace of the geological cross section.

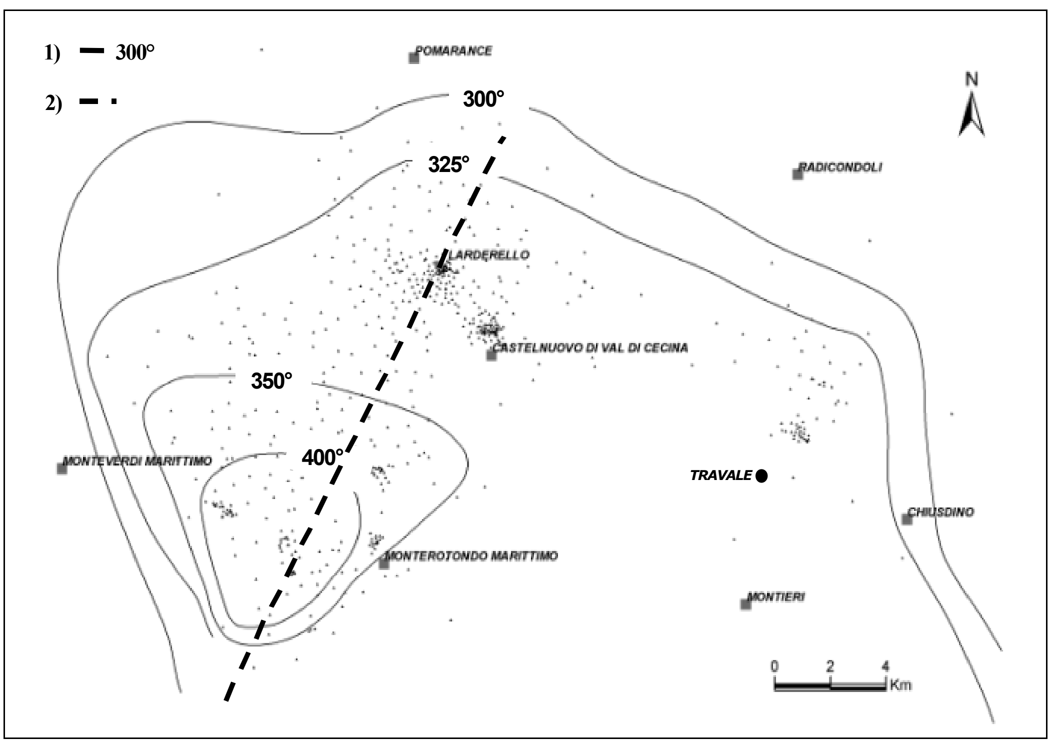



FIG. 5: Temperature distribution at 3000 m (b.l.s.) in the methamorfic besement of the Larderello – Travale geothermal field. 1) Temperature distribution at 3000 m depth (b.s.l.). 2) Trace of geological cross section

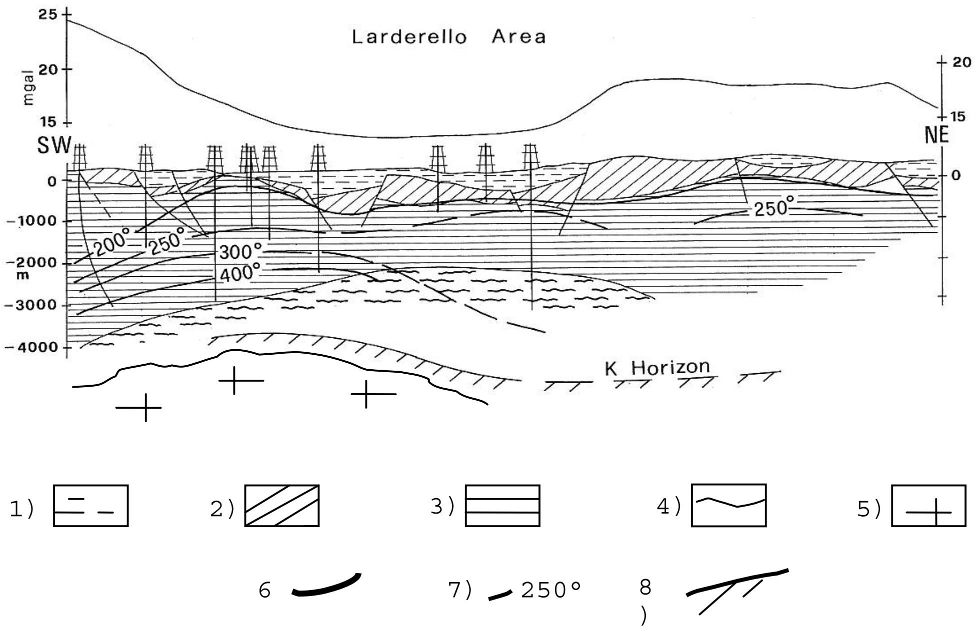



FIG. .6. Geological cross section through Larderello-Travale geothermal field (trace in Fig.5). LEGEND: 1) Neogenic sediments; 2) Flysch complex; 3) Evaporitic and metamorphic formation; 4) Gneiss group; 5) Granite; 6) Bouguer anomaly (mgal); 7) Isotherm (°C); 8) Seismic horizon.

## Geothermal Fields in Tuscany

At present, energy production from geothermal resources in Italy (about 700 MW) is only from Tuscany. The geothermal fields of the Larderello-Travale and Mt. Amiata areas (Bagnore and Piancastagnaio) have considerable similarities from the geological and geothermal points of view. Both geothermal areas are characterized by:

- a cap rock represented by flysch facies formations ("Ligurids") and, where present, by Neogene formations;
- a shallow reservoir hosted in the carbonate and anhydritic formations of the Tuscan Nappe;
- a deep reservoir hosted in the metamorphic units.

With respect to the volcanic Mt. Amiata region, the Larderello -Travale area is characterized by large-scale natural steam and gas manifestations, no volcanic outcrops, and many granitic intrusions at depths ranging from 2000 to 4000 m.

The geothermal fluid of the Larderello-Travale field is a superhead steam, with the following chemical composition (m moles/l): $H_2O$ 975,8; $K_2$ 0,5; $CH_4$ 0,32; $CO_2$ 22,71; $H_2S$ 0,46; traces of gas rare.

The first drillings were carried out close to the natural manifestations and then along the structural high of the carbonate reservoir. The temperature distribution at the top of the shallow reservoir shows highest values (> 250°C) in correspondence with structural highs of the carbonate–evaporitic formations, where the most favorable permeable conditions pertain (Fig. 4).

On the contrary, the temperature distribution at 3000 m b.s.l. (Fig. 5) shows a large temperature anomaly (about 400 $km^2$) that testifies a single deep geothermal system enclosing both the Larderello and Travale fields.

At the level of the top of the shallow reservoir, a low temperature area, due to meteoric water circulation in the permeable carbonate outcrops, separates the Larderello field from the Travale one.

Shallow and deep reservoirs are a superheated steam geothermal system and are in vapor static equilibrium. The maximum temperature (437 °C at 3225 m) was measured in a dry well located in the southern part of the Larderello field, while the maximum gas pressure (> 300 bar) was found in a productive well located in the same thermal anomaly.

Generally, the deep productive steam horizons have been found in permeable levels of the metamorphic formations (Fig. 6) with temperatures ranging from 300–350 °C and steam pressure ranging from a few bars, in the most drained zones, up to 60-70 bars, in the less drained ones.

In the southeastern part of the Travale field, productive deep horizons have recently been reached also in old granitic intrusion (see Fig. 6).

Unlike the Larderello–Travale, the two Mt. Amiata geothermal fields (Bagnore and Piancastagnaio) are characterized by shallow steam/gas and a water dominated reservoir. The chemical composition (mg/l) of the water is: Na 700; K 150; Cl 1185; $SiO_2$ 432; $CO_2$ (tot) 28750; $H_3BO_3$ 4390; $NH_4$ 555; $H_2S$ 860.

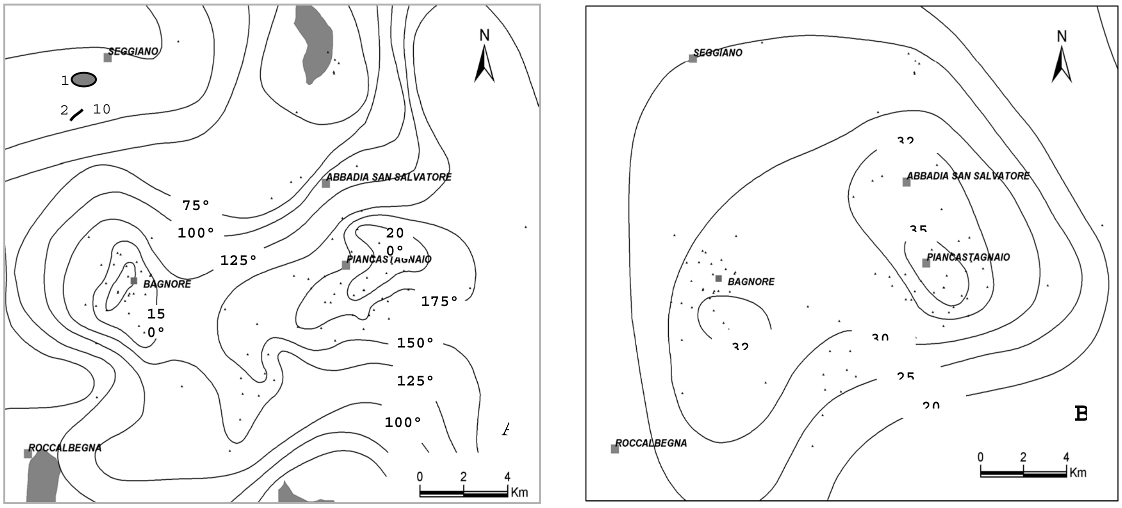



FIG. 7. Temperature distribution in the Mt. Amiata geothermal field.
A) Top of the carbonatic resevoir. B) 3000 m (b.s.l.), in the metamorphic basament

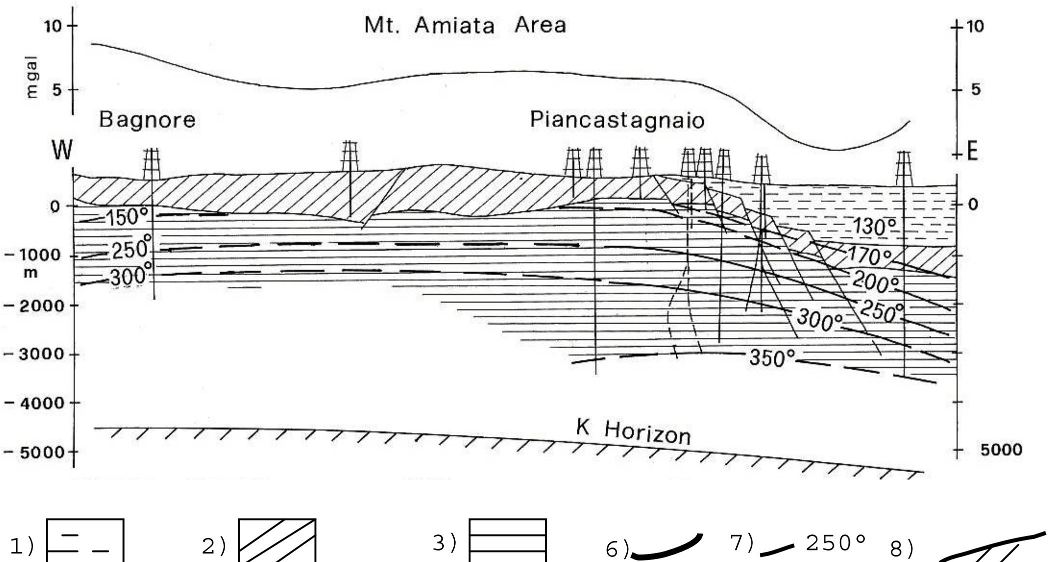



FIG. 8: Geological cross section through the Bagnore and Piancastagnaio geothermal fields (Mt.Amiata). 1) Neognic sediments; 2) Flysch complex; 3) Evaporitic and metamorphic formation; 4) Bouguer anomaly (mgal); 5) Isotherm (°C); 6) Seismic horizon.

Both the fields correspond to a positive structure of the carbonate–evaporitic reservoir (400–800 m depth), with temperatures of 150 – 210° C (Fig. 7A) and pressure of 22–42 bar.

Also in the Amiata fields, the deep exploration evidenced a deeper geothermal reservoir (2500–3500 m), in the metamorphic basement that is made up of Paleozoic carbonate–phyllites formations. This is a water dominated reservoir in hydrostatic pressure connection with the shallow one.

As with the shallow temperature distribution, at 3000 m depth the highest temperatures are found in the Bagnore and Piancastagnaio fields (Fig. 7B). In the latter, a temperature of 427 °C has been measured at 3826 m depth.The productive fractures system in the metamorphic basement is widespread throughout a big thickness of rocks with temperatures of 300–360 °C and pressures of 190–250 bar (Fig. 8). In the Mt.Amiata area, the deep wells (< 4000 m) did not reach granitic rock intrusion but just a thick carbonate thermometamorphic aureole.

In order to define targets for deep exploration, many seismic reflection profiles and vertical seismic profiles have been performed. Both in the Larderello-Travale and Mt. Amiata areas, seismic data showed many reflectors which can be correlated to fractured/permeable levels and the presence, at depths of about 3-5 km, of a continuous seismic marker (K horizon). This is characterized by large amplitude and frequency anomalies (BATINI *et alii*, 1978; GIANELLI *et alii*, 1988) and seems to be in agreement with the presence of geothermal anomalies.

Many geological interpretation have been proposed for this horizon:

- rheologic behavior due to a brittle/ductile crustal transition (CAMELI *et alii*, 1993);
- a kinematic belt in the lower part of the brittle crust (BELLANI *et alii*, 2004);
- a thermometamorphic aureole of a Recent (Quatenary) granitic intrusion (BERTINI *et alii*, 2004 in press).

The Larderello–Travale and Mt. Amiata fields are also characterized by a considerable crustal uplifting (MARINELLI, 1975). In fact, the most recent marine sedimentary formations of Quaternary - Middle Pliocene age, that filled the main Neogene sedimentary basin, reach an elevation of 600 m in the Larderello and more than 800 m in that of Mt. Amiata. Also the two thermal anomalies, on the basis of the heat flow data, are relatively comparable both in intensity and extent.

## Geothermal Production in Italy

Enel is the only operator in energy production from geothermal resources in Italy, and also one of the main suppliers of geo-heat. Geothermal power plants in operation are located in the Larderello -Travale and in the Mt. Amiata areas (southern Tuscany) where 32 units, all remote controlled, are in operation with a total running capacity, as of January 2004, of 700 MW. The energy production in the year 2003 reached 5 TWh, representing 25% of energy needs in Tuscany (Fig. 9).

A total of 280 production wells and 60 reinjection wells are in operation in the Larderello, Travale and Mt. Amiata areas with 190 km of steam pipelines and 250 km of water pipelines.

In addition to power production Enel is also engaged in direct uses heat supply for 1260 TJ/yr (45% greenhouses, 34% space heating, 20% industrial heat process and 1% fish farming) and in $CO_2$ supply for the food industry (32,000 t/yr).

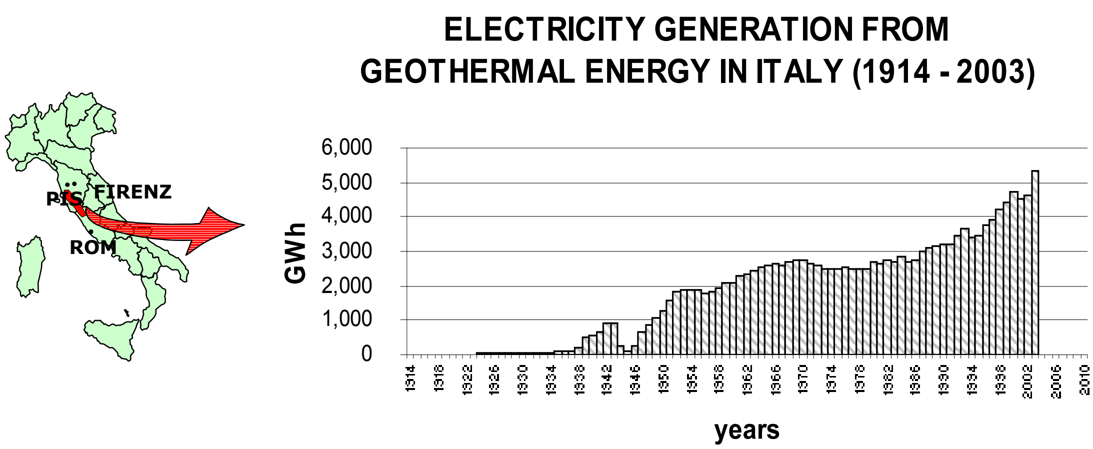



FIG.9: Energy production growth in Italy

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