R&D OF DEEP GEOTHERMAL RESOURCES IN ITALY

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ABSTRACT

In the framework of the exploration and exploitation programme of deep geothermal resources in Italy, since the end of the 1970s over 140 wells deeper than 2,500 m have been drilled in different areas of central Italy (Tuscany and Latium).

This activity has made it possible so far to find significant amounts of additional geothermal resources and to expand considerably the areas of interest. It has also allowed to increase the knowledge of the geothermal systems, supplying useful indications for the future programmes of deep exploration.

1. INTRODUCTION

Aside from a few sporadic previous attempts, the systematic exploration and exploitation of deep geothermal resources in Italy began in the late 1970s (Cappetti et al., 1985; Barelli et al., 1995/b).

Intensive exploitation of shallow geothermal reservoirs (depth 500-1000 m) in the 1950s and '60s, increased geological and geophysical data, and progress made in drilling technology have encouraged ENEL to implement a wide-ranging deep drilling programme. Particularly seismic surveys revealed the existence of deep reflections, the deepest and most continuous of which is the so called "K" horizon.

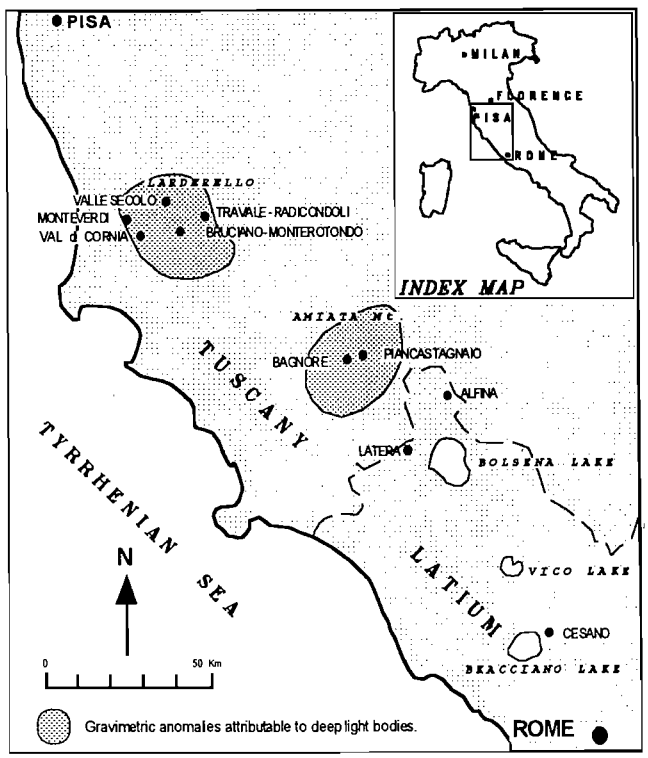

Fig. 1 - Zones interested by R&D of deep seated geothermal resources in Italy.

All the data collected suggested that exploitable fractured levels could exist at depth with fluid at temperature and pressure higher than the ones already under exploitation.

The drilling programme was mainly developed in Tuscany and secondarily in Latium, north of Rome (Fig. 1).

To date, more than 140 wells have been drilled to depths of over 2,500 m; about 100 of them are deeper than 3000 m and 24 of these are deeper than 4,000 m.

Most of the deep wells are directional.

This extensive deep drilling has shed light on geological, thermal and hydrogeological situations that are different from one zone to the next and are often of considerable scientific and industrial interest.

The aim of this work is to offer an update on this activity by outlining the different situations and their prospects for future development.

In Tuscany the deep geothermal resources exploitation involved the geothermal fields of Larderello (Monteverdi, Val di Cornia, Bruciano - Monterotondo, Valle Secolo zones), Travale - Radicondoli and Mount Amiata (Bagnore and Piancastagnaio zones).

The deep wells drilled in northern Latium regard the Alfina, Latera and Cesano fields (see Fig.1).

2. LARDERELLO GEOTHERMAL FIELD

2.1 Monteverdi

The Monteverdi zone is located on the western edge of Larderello geothermal field. The explored area extends over about 25 km^2 and lies between the H.F. contour-lines of 200 and 600 mW/m^2 (Baldi et al. 1995/b); the temperatures at a depth of 3,000 m are around 350°C (Fig.2)

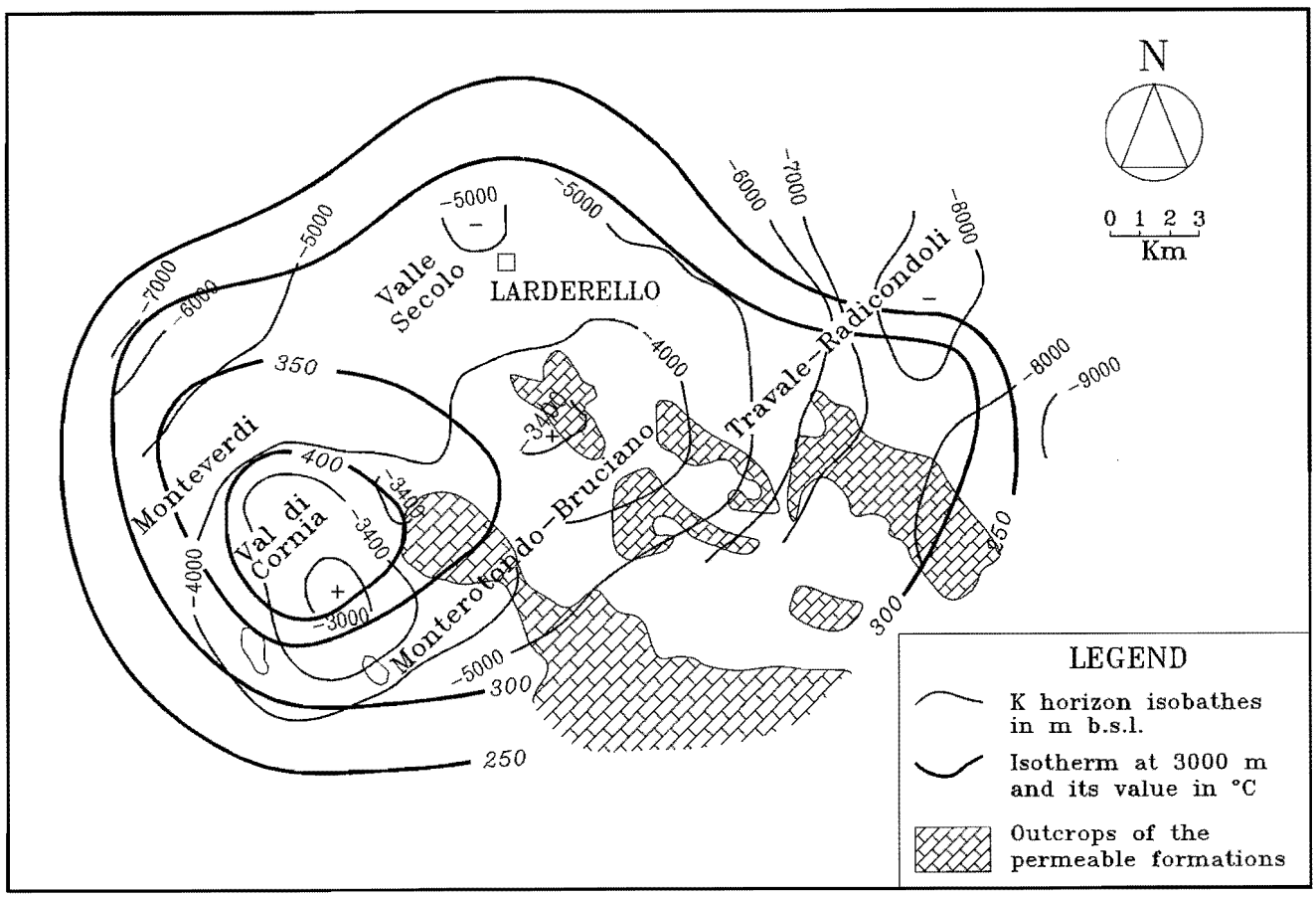

Fig.2 - Deep drilled zones in Larderello and Travale-Radicondoli geothermal fields.

In this zone about 20 wells, mostly directional and with a maximum depth of 3,910 m, have been drilled so far. Of these, 14 have proved to be productive and the steam will feed two 20 MWe power plants that, under construction, will come on line by 1997.

The stratigraphic sequence, from the top down, is made up of:

- Mainly argillaceous Neogene formations (U. Mioc. - L. Plioc.); flysch facies formations (Ligurid Units) (L. Cret. - Eoc.); total thickness 800-1000 m.
- 'Tectonic Wedges Complex' (Paleoz. - Trias), made up of an irregular phyllite, quartzite and quartzose conglomerate assemblage; the thickness is variable, averaging 200-300 m; the carbonate-anhydritic formations, that makes up the shallow reservoirs of the Larderello field, are absent here.

- 'Polymetamorphic Complex' (Paleoz.), composed of phyllites (mean thickness 500 m), micaschists (mean thickness 600 m), and gneisses, locally crossed by granitic dykes.

In this zone the Tectonic Wedges Complex is not very permeable, and together with the neogenic and flysch facies formations it forms the cap-rock. The potential reservoir is represented by the Polymetamorphic Complex where the presence of fractured layers extends over a wide interval of metamorphic rocks (depth ranging from 1,800 to 3,500 m) and seems to be independent of lithology.

Two main fracturing mechanisms may have acted over time, the first linked to a stress field controlled by magmatic intrusions with hydraulic fracturing phenomena, followed by a second marked by a regional stress field of the tensional type running in a NE-SW direction.

The reservoir is characterized by pressures ranging between 60 and 75 bars and temperatures between 270° and 350°C. These thermodynamic conditions are responsible for the presence of a saturated fluid at the top of the reservoir, which passes to a superheated fluid towards the bottom.

The relatively high pressures indicate a poor lateral connection with the field under exploitation in the nearby, where pressures at depth do not exceed 10-30 bars owing to field exploitation.

The Monteverdi zone probably has thermodynamic conditions similar to the initial ones of the Larderello geothermal area.

2.2 Val di Cornia

This zone is located east and south-east of the Monteverdi one (see Fig.2). Unlike Monteverdi, the Val di Cornia zone is characterized by the presence beneath the cap rocks, again mostly composed of argillaceous Neogene and flysch facies formations with thickness ranging from 300 to 900 m, of carbonate-anhydritic formations belonging to the Tuscan Unit.

These last have a thickness of about 300 m and represent the shallow reservoir that has been exploited for several years now.

Below this shallow reservoir there is a palaeozoic metamorphic sequence composed of phyllites, micaschists and gneisses. These formations, which constitute a relative structural high in Val di Cornia, form the deep reservoir which has been reached by around 20 wells with a maximum depth of about 4,200 m.

In this zone the success ratio and the specific productivity of deep wells are the lowest in the Larderello geothermal field.

The thermodynamic conditions of the shallow reservoir are those of a superheated steam, with temperatures of about 240°C and pressures around 20 bars.

The few fractures in the deep reservoir are mostly located below 2,000 m.

Also the deep reservoir is characterized by superheated steam with stratum pressure of 40-50 bars and formation temperatures, below 2,500 m, higher than 350°C. In some points temperatures of over 400°C have been recorded at depths of about 3,000 m.

In few cases overpressured gaseous fluids have been found.

The Val di Cornia zone, with respect to the other ones, features the highest temperatures at the same depths (see Fig. 2).

As can be deduced from the above data, the deep reservoir in this zone displays low permeability on average.

It is likely that one of the causes of this low permeability is the high temperature. At this temperature level, the rocks probably have a ductile or semiductile behaviour, causing a gradual attenuation of the permeability.

It can be observed that the seismic reflection 'K' horizon (present all over western Tuscany and considered a sort of brittle/ductile rheological limit) is found in this zone at a lower depth than in the rest of Larderello and Travale-Radicondoli fields (Cameli et Al., 1993).

2.3 Bruciano-Monterotondo

The Bruciano-Monterotondo zone is located east-south-east of Val di Cornia and represents the south-east margin of Larderello field so far investigated.

This zone has geological and structural characteristics that are in part similar to those of the previous zone, in part different.

The similarities are the presence of a shallow reservoir composed of the chiefly triassic carbonate-anhydritic formations of the Tuscan Unit and the underlying metamorphic sequence (phyllites, micaschists, gneisses) which constitutes the deep reservoir.

The differences are the greater completeness and thickness of the Tuscan Unit, the proximity to a broad area where this Unit outcrops. This area is both an area of cooling and of potential field recharge by infiltration of meteoric water.

As demonstrated by data from the deep wells, there is a sufficient separation between the large area of infiltration and the deep reservoir to keep it from cooling. This may have considerable importance for the prospects of developing deep resources.

Thirteen deep wells have been drilled in this zone, 12 of them productive and one dry. The wells have an average flow-rate of about 30 t/h.

Most of the productive fractures are located between 2,000 and 3,000 m depth. While the temperature and pressure of the shallow reservoir in the Bruciano-Monterotondo zone are about 200°C and 10 bars respectively, the temperature of the deep reservoir is around 350°C and the pressure ranges between values of 50 and 65 bars.

2.4 Valle Secolo

Valle Secolo is one of the most exploited zones as regard shallow reservoir, where the stratum pressure has fallen to around 5 bars.

Below the cap rock, composed mostly of Neogene and flysch facies formations (Ligurid Unit), the shallow reservoir is represented by the chiefly carbonate-anhydritic formations of the Tuscan Unit and by the top of the underlying metamorphic sequence.

The reservoir is located at a depth of about 500-800 m and displays very high permeability.

The metamorphic sequence is fractured at various depths, especially between 2,000 and 3,000 m.

Nine deep wells have been drilled, six of them are productive, with an average output of around 25 t/h of superheated steam.

The temperatures in the shallow reservoir are about 240-250°C. In the deep reservoir, temperatures are lower than 300°C; the pressure of about 30 bars is affected by the long exploitation of the shallow reservoir.

3. TRAVALE-RADICONDOLI GEOTHERMAL FIELD

The Travale-Radicondoli field is crossed by an important geologic structure, a NW-SE trending master fault system, that separates the Neogene sedimentary basin (Graben) of Radicondoli to the east from a structural high (Horst) of flysch facies formations (Ligurid Units) and from the underlying, mostly carbonate-anhydritic formations of the Tuscan Unit, to the West.

These formations make up the shallow geothermal reservoir which has been initially explored and exploited in corrispondence of the Horst.

Investigation of the upper part of this reservoir gave negative results caused by inflow of meteoric water. Exploration and exploitation of the same reservoir continued at greater depth also inside the Radicondoli Graben. Afterward, R&D activities were extended to deep layers (to over 4,000 m depth) within the metamorphic sequence.

These efforts also regarded areas in which limestones and anhydrites outcrop. Cooling of these formations by meteoric water resulted to be confined to the shallow layers. Infact impermeable horizons separate the shallow layers from deep fractured ones in the metamorphic complex, determining an increase of temperatures up to values of 330-350°C (Barelli et Al., 1995/a).

In this field the temperature at 3,000 m is considerably lower than the temperature at the same depth in the SW part of Larderello field (see Fig.1).

The degree of fracturing of these deep reservoir layers (depths of about 4,000 m) is unusually high as well as the productivity of the wells.

About 20 deep wells have been drilled, over half of them are productive (mean productivity is approximately 50 t/h).

The fluid produced by these wells is superheated steam. The stratum pressures of the deep reservoir are around 70-75 bars.

4. MOUNT AMIATA GEOTHERMAL FIELDS (Bagnore and Piancastagnaio)

In the Mount Amiata volcano area (Fig.3), exploration and exploitation of geothermal resources in the 1950s and '60s were focused on shallow geologic structures (400-1,000 m) constituted, as in Larderello area, by prevalently carbonate-anhydritic formations of the Tuscan Unit (Bertini et al., 1995).

The fluids are characterized by temperatures ranging between 160°C (Bagnore) and 220°C (Piancastagnaio); the fluids had initially high gas content with stratum pressure between 23 and 40 bars respectively.

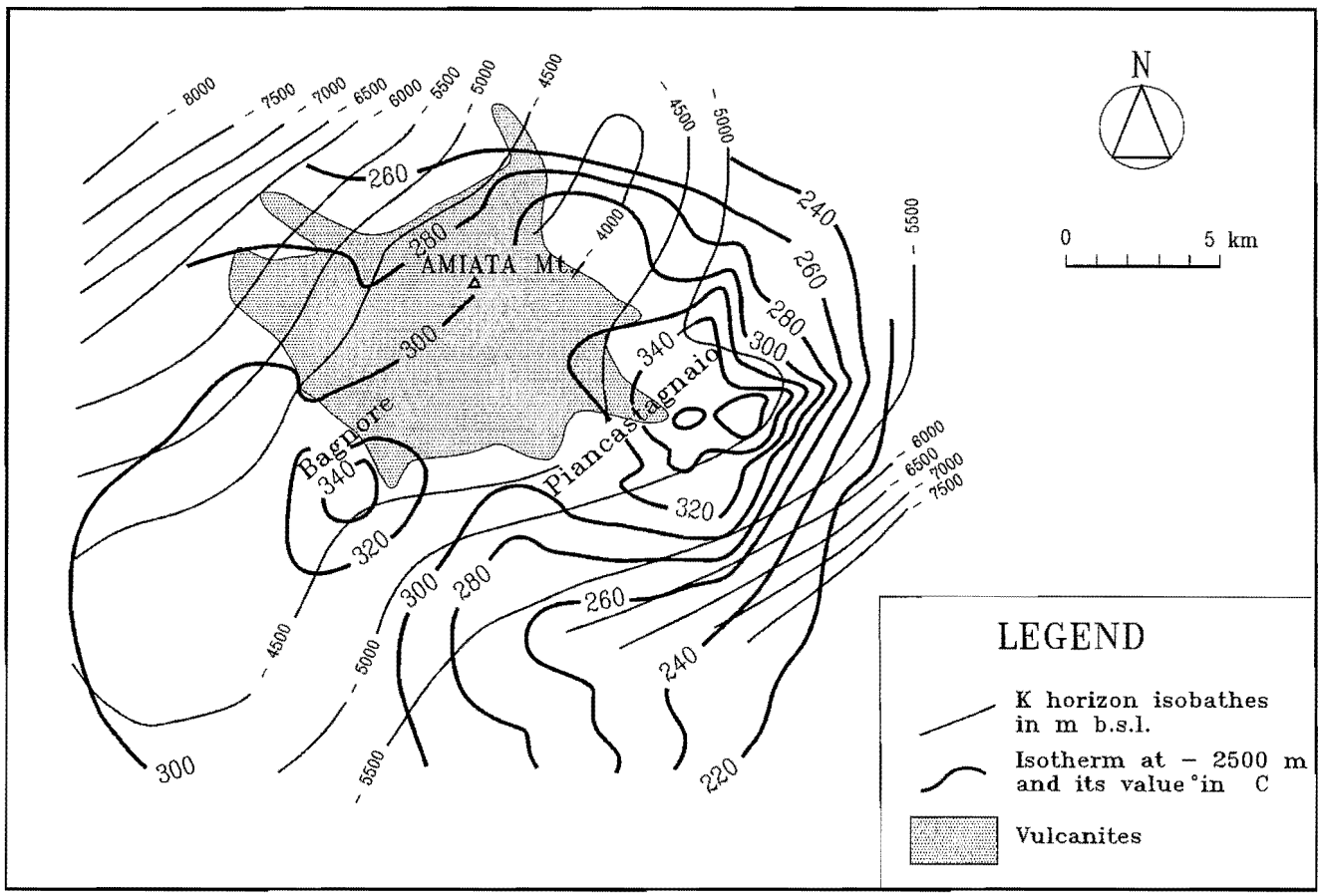

Fig.3 - Deep drilled zones in Mount Amiata geothermal fields.

At the end of the 1970s an intensive deep drilling programme was begun; so far 35 deep wells have been drilled, 27 of them in the Piancastagnaio field.

The exploitation of deep resources in the Mount Amiata volcano area has had considerable success. The percentage of productive wells is very high (almost 90%), as well as the mean productivity of the wells (>30 t/h of steam). This has made it possible to increase the installed capacity by 80 MWe.

At both Bagnore and Piancastagnaio, deep wells have shown the existence of a large deep reservoir (between 2,000 and 3500 m depth), characterized by good permeability due to fracturing, stratum pressures of about 200-250 bars and temperatures around 350-360°C (see Fig.3).

This is a water-dominated reservoir that, although hydraulically connected with the shallow one, is separated from it by a low permeability layer 800-1,000 m thick.

Thus, although structurally similar to the Larderello and Travale-Radicondoli geothermal system (the reservoir formations are analogous), this system has different thermodynamic characteristics.

In the northern part of Mount Amiata a well deeper than 4,800 m has pointed out the presence of impermeable rocks with a thickness of about 4,000 m, characterized by a rather low, but constant thermal gradient (0.7 °C/10 m). Below this depth there are still fractured levels with fluids having pressure of about 330 bars and temperature higher than 320°C.

5. NORTHERN LATIUM GEOTHERMAL FIELDS

The geothermal framework in northern Latium is quite different from that in Tuscany (Baldi et al., 1993). The exploration and exploitation activities carried out in this region in the 1970s and '80s showed the presence of water-dominated geothermal systems characterized by temperatures ranging from 140°C at Alfina to 220-230°C at Latera and Cesano fields.

These resources are stored in mesozoic carbonate reservoirs (Tuscan and the Umbrian-Sabina Units) beneath a cover composed mainly of clayey (U. Mioc. - Plioc.) and flysch facies formations (Ligurid Unit) at depths ranging between 500 and 1,000 m (Buonasorte et Al., 1995).

Numerous deep wells have been drilled in the Alfina, Latera and Cesano fields, with little success. These wells have shown that in Latium the carbonate formations are always very thick, often due to the presence of several overthrusts and folds. Metamorphic rocks have not been encountered by wells up to the maximum drilled depths (4,826 m).

The degree of fracturing of the reservoir formations is generally low, often because of self-sealing processes. The permeability of these rocks is therefore usually very low in all the investigated zones, so most of the wells are either dry or non-commercial.

6. KNOWLEDGE AND RESULTS

The deep drilling activity has considerably increased the knowledge of the deep geothermal systems of central Italy, supplying useful indications for the further development of this activity. In summary, the main elements of knowledge are the following:

- The geothermal anomalies of Larderello, Travale-Radicondoli and Mount Amiata, at depth, are much wider than originally thought. These anomalies do not end with the outcroppings of reservoir rocks that, up to a few years ago, represented the edges of the fields. Basically, these anomalies are separate at the surface but 'unified' at depth, where they become single large anomalies (Baldi et Al., 1995/a).
- The heat source that underlies these anomalies is linked to recent granitic bodies. In various zones, from Monteverdi in the west to Travale in the east, deep wells have encountered granitic

dykes and bodies ranging in age between 3.7 and 0.5 MA. This demonstrates the presence of a phenomenon of prolonged granitisation of the crust.

- The above is also in agreement with two important geophysical features: the tuscan geothermal areas fall within large negative gravity anomalies, explainable only by the presence of light bodies within the metamorphic basement (see Fig.1). Moreover, earthquake tomography (Batini et Al., 1995) clearly indicates the presence of low-velocity bodies below Larderello and Travale-Radicondoli areas, attributable to acidic intrusions that have not yet cooled.
- Seismic reflection surveys have also shown a strong and continuous seismic reflection horizon ('K' horizon) that, in the most thermally anomalous areas, nears the surface like a dome (see Figs. 2 & 3). This horizon might indicate the transition between an upper crust with a brittle behaviour and a lower crust with a more ductile behaviour. Seismic reflections are often present inside the metamorphic formations whose geological significance is not always easy to identify.
- The fracture-derived permeability of the deep metamorphic reservoir in Tuscany is not as high or diffuse as that of the shallow reservoir; however, it is often sufficient to allow good and sometimes excellent production. Nevertheless, the permeability tends to disappear when the temperature rises above 350-370°C. Deep exploration has reaveled that, within a temperature range of 300°-350°C, it is possible to find fractured layers up to depth of 5,000 m, both in sedimentary and metamorphic rocks.
  The deep layers of Travale-Radicondoli and Val di Cornia are a case in point. In the former, where temperatures lower than 350-370°C exist beyond 4,000 m, there are fractured layers even at this depth; in Val di Cornia, where such temperatures are present at little more than 2,000-2,500 m, the permeability tends to disappear beyond this depth.
- Despite many attempts of interpreting jointly different kind of data, it has not always been possible to identify the causes that determine the fracturing of deep reservoirs and their distribution and geometry.
- From an idustrial point of view, R&D of deep geothermal systems have provided on the whole rather good results. We can estimate that more than 200 MWe have been acquired up to now by deep seated resources. Nevertheles these results cannot be generalized to all the areas with high temperature anomalies. These could be characterized by low permeability caused by too high temperature or by self-sealing phenomena.

7. PROSPECTS

The knowledge gained on Italian geothermal systems makes it possible to affirm that the exploration and exploitation of additional deep resources have good prospects, especially in Tuscany. Those prospects regard:

- The margins of the exploited fields of Larderello, Travale-Radicondoli and Mount Amiata, which still display possibilities for extending the drilling; in some of these areas deep exploratory wells have been already planned;
- New areas within the above mentioned large geophysical anomalies (negative gravity anomalies, seismic velocity anomalies, etc.), characterized at the surface by outcrops of rocks belonging to the shallow reservoir (Tuscan Unit) and therefore cooled by meteoric water;
- Other areas characterized at the surface by H.F. values higher than 150-200 mW/m^2 which display favourable conditions at depth in certain geological and structural situations for the accumulation of geothermal resources of industrial interest (Baldi et Al., 1995/a).
- Methodological research activities must be necessarily developed in order to minimize the mining risk in deep exploration. Efforts will be focused on the reconstruction of fracturing models by mean of geological and structural studies and advanced geophysical methods.

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