RESULTS OF DEEP DRILLING IN THE LARDERELLO-TRAVALE/RADICONDOLI GEOTHERMAL AREA

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ABSTRACT

Deep dnlling showed that the Larderello and Travale-Radicondoli geothermal fields, which for many years were regarded as two independent systems, belong to a single geothermal area.
At 3000 m below sea level the 300°C isotherm covers approximately 400 km^2 and includes both fields and the area in between.
Productive levels have been discovered in the metamorphic basement to a depth of about 4000 m.
The success ratio of the deep drilling has been about 60% with flowrates ranging between 8 and 16 kg/s (average values per productive well in the areas of Larderello and Travale-Radicondoli).
The geothermal system was found to be steam-dominated everywhere.
The shallow well drainage has extended to depths of 3000 m in the most exploited areas, while in those not affected by drainage the reservoir pressure is still about 7 MPa.

1. INTRODUCTION

The Larderello and Travale geothermal fields, about 15 km apart, were considered for many years to be two independent geothermal systems.
Drilling in the Larderello field dates back to the early 19th century, while in the Travale-Radicondoli field it began about one hundred years later.
The first Larderello wells, located near the natural manifestations, were drilled to tap the boric waters present in the shallow layers of the cover formations.
Later, drilling was deepened to reach the reservoir top, a few hundreds meters down.
To increase fluid production, the drilled area was extended to the borders of the productive areas, with wells reaching the reservoir top at a maximum depth of about 1500 m.
In the late 1970s, a deep exploration program was started to investigate the existence of deeper permeable layers with fluids at temperatures and pressures higher than the ones already under exploitation.

2. GEOLOGIC SETTING AND TEMPERATURE DISTRIBUTION

The geothermal area of Larderello and Travale-Radicondoli is located in correspondence to a structural high of the Tuscan Nappe (radiolarites, marls, limestones and anhydrites) and Tectonic Wedges Complex (anhydrites, phyllites and quartzites) which constitute the main reservoir. This reservoir is characterized by high secondary permeability at the top.
The above formations irregularly overlie a metamorphic substratum made up of phyllites, micaschists and gneiss. The deep wells revealed the presence of fractured layers inside this substratum with an increase of temperature and pressure with depth.
The Liguridi Complex (specifically Flysch) and Neogene sediments cover the reservoir formations and act as cap rock for the geothermal system.
In the last 15 years, extensive drilling has led to greater knowledge of the temperature distribution, both areally and at depth.
The present thermal knowledge is summarized in the maps of Figures 1, 2 and 3.
Figure 1 shows the isotherms at the reservoir top, which is seldom deeper than 1000 m. This map highlights some maximum temperatures of over 250°C corresponding to the main structural "highs" of the reservoir. These structural highs are also the most permeable areas.

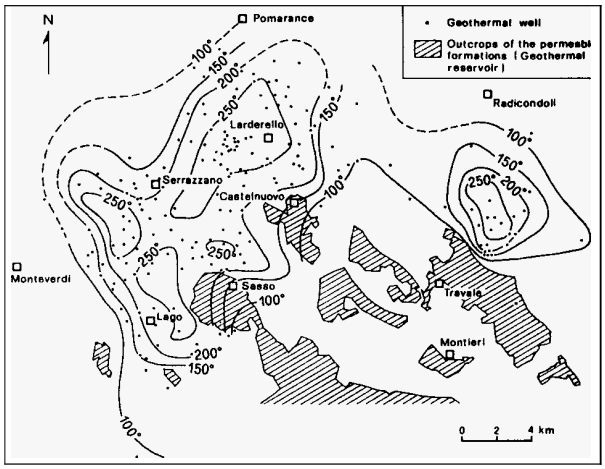

Figure 1. Temperature (°C) distribution at the reservoir top.

Southward, the temperatures at the reservoir top decrease to values of less than 100°C due to the inflow of meteoric water through the reservoir formation outcrops.
The thermal attenuation that occurs in the other directions marks the boundary of the geothermal system: this phenomenon is due to a sharp permeability reduction.
The temperature distribution at depths of 2 and 3 km b. s. l. (Figures 2 and 3) is more uniform than at the reservoir top (Figure 1). This outline is well defined in the northern area between Larderello and Travale where deep wells have been drilled, whereas it is less clear in the southeastern sector, where environmental constraints impede geothermal activities (Figure 3).
The schematic geologic sections through the whole geothermal area and the temperature distribution are given in Figure 4.
In the high permeability zones, the temperature is homogeneous because of fluid circulation and the isotherms are more widely spaced, whereas in the low permeability zones the isotherms are closer to each other as the heat transfer occurs only by conduction.

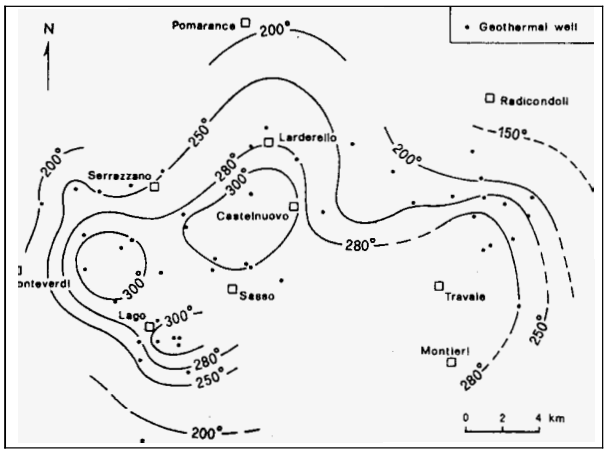

Figure 2. Temperature (°C) distribution at the depth of 2000 m b.s.l.

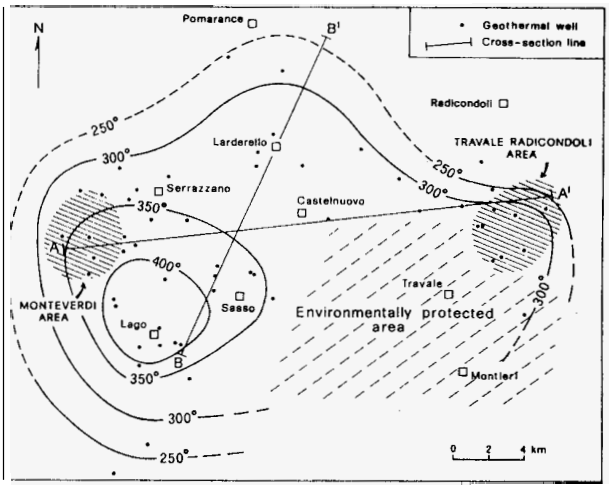

Figure 3. Temperature (°C) distribution at a depth of 3000 m b.s.l. and locations of the geologic sections.

In the zones where temperatures above 350-370°C have been measured, the wells did not cross permeable levels. It is believed that the 350°C isotherm is the bottom of the geothermal reservoir since, below this limit, the temperature increases with a gradient typical of a conductive heat flow regime.

At Travale-Radicondoli and in the Larderello central zone the deepest wells (about 4000 m) have not yet reached the reservoir bottom, whereas in the Lago zone it was found at a depth of about 3000 m.

3. PRESSURE DISTRIBUTION

The reservoir pressures at the start of exploitation of Larderello field are unknown.

This lack of data has been partly overcome by observing that steam pressure in the reservoir can often be calculated from the water level in a well after a fractured horizon is met during drilling.

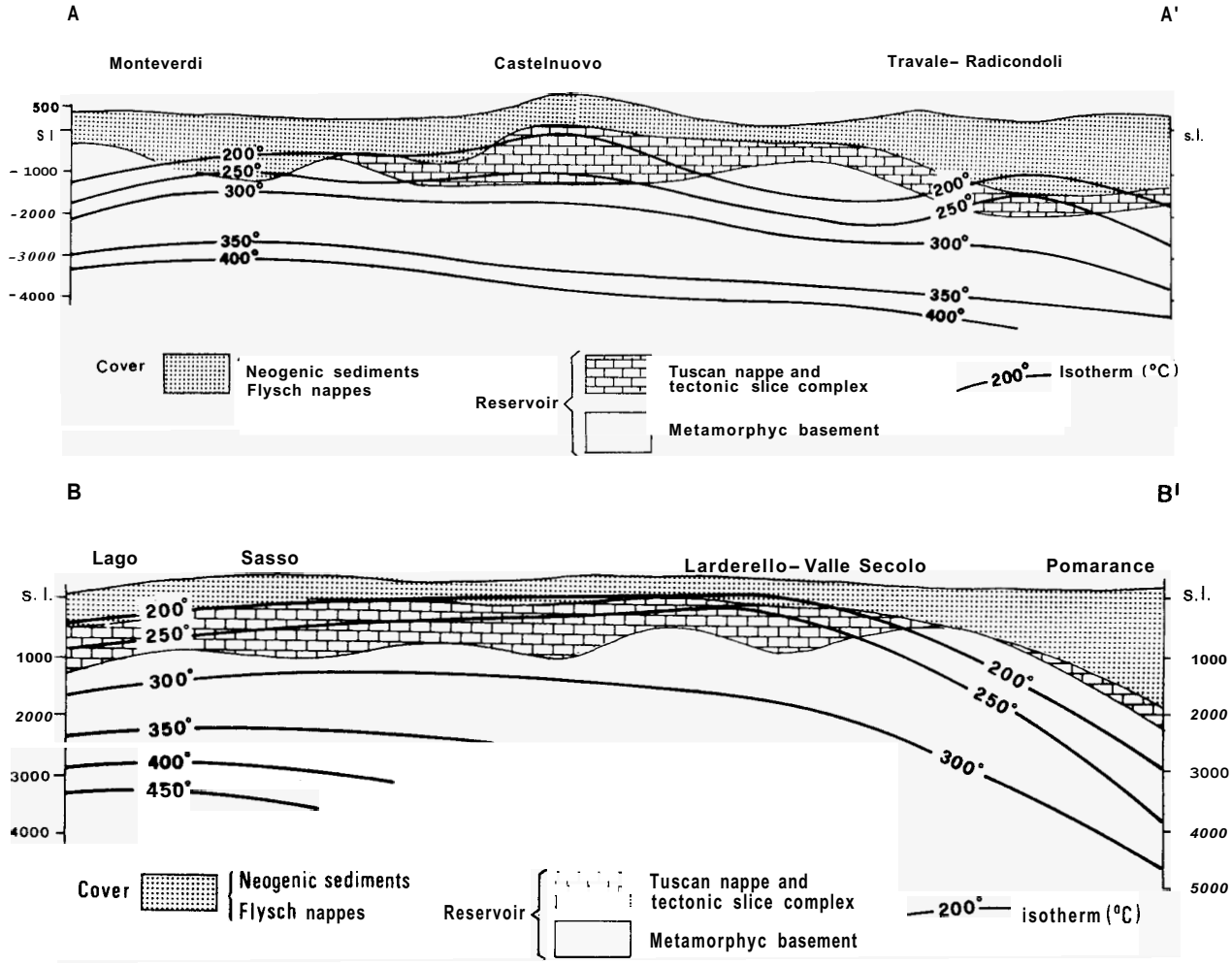

Figure 4. Geologic sections and temperature distribution.

The first water levels measured in the wells of Larderello gave a pressure of about 3 MPa at reservoir top. This value is confirmed by a shut-in test performed in 1942.
The first data on pressure dismbution vs. depth were obtained in 1961, when a deep well was drilled in the central part of Larderello. This 2703 m deep well crossed the fractured zones of the metamorphic basement, showing an increase of temperature and steam pressure with depth.
In the 1970s a deep exploration program was started in the central zone and at the margins of the Larderello field. The results of the deep drilling activity are summarized in Table 1.
These deep wells showed the presence of productive horizons inside the metamorphic basement at depths of 2500 m to 3500 m and allowed reconstruction of the pressure dismbution all over the explored area.

Table 1. **Deep** wells drilled in Larderello field

Period	Number of drilled wells #	Average well depth [m]	Average flowrate per productive well kg/s	Success ratio %
1971-May 1994	82	3350	8.5	60

In the Travale-Radicondoli field the deep exploration started in 1984. At present, 13 wells have been drilled, with a 60 % success ratio, the same percentage found in Larderello geothermal field. The average flowrate of the productive wells was 16kg/s, which is twice the value observed in the Larderello field. These wells crossed productive horizons inside the metamorphic basement at depths ranging from 2500 to 4000 m. Flowrates as high as 25 kg/s have been found at the unusual depth of 4000 m.
The present pressure dismbution at the reservoir top for the whole study area is shown in Figure 5.

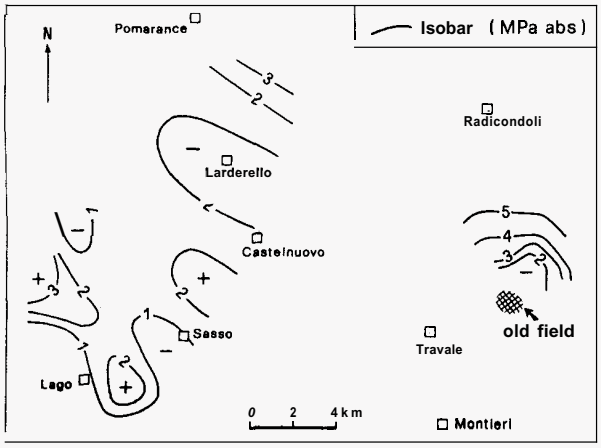

Figure 5. Pressure distribution at the reservoir top.

As for the pressure distribution with depth, different situations exist in different areas.
At Monteverdi and Lago, located at the western and southern borders of Larderello geothermal field, and at Travale-Radicondoli, located at the east margin, the poor connection between the various productive levels has prevented the drainage from spreading below the currently exploited layers (Figures **6, 7** and **8).**
On the contrary, at Larderello-Valle Secolo, which is the area with the highest and most widespread permeability, drainage effects extended to at least 3 km (Figure 9).
On examining the above figures, we can observe that the pressure at the reservoir top is not uniform all over the area because it is controlled by permeability and exploitation history (Figure 5).
Conversely, the deepest pressure values are more uniform.

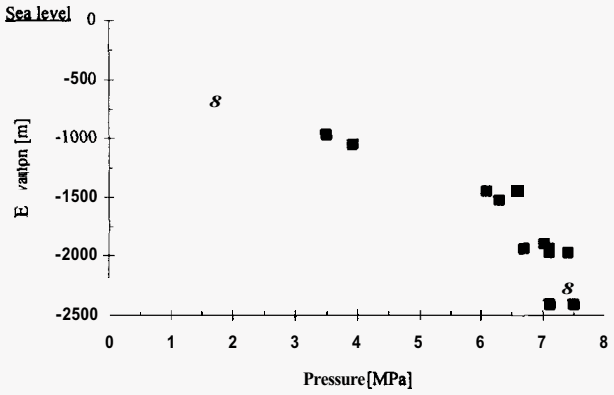

Figure 6. Reservoir pressure vs. depth in the Monteverdi zone.

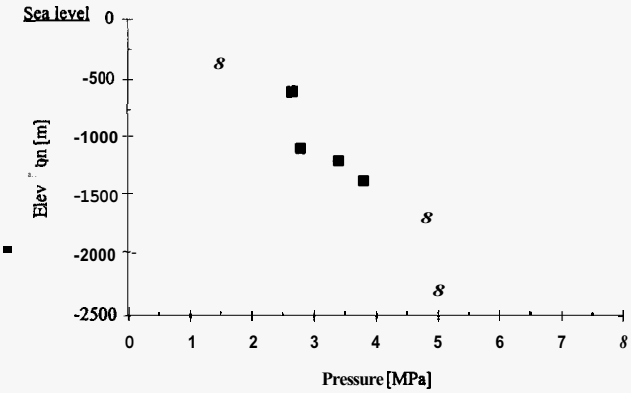

Figure 7. Reservoir pressure vs. depth in the **Lago** zone.

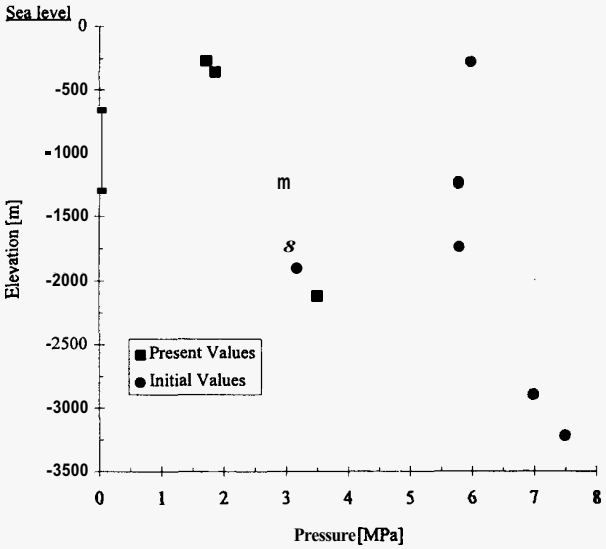

Figure 8. Reservoir pressure vs. depth in the Travale-Radicondoli zone.

It is important to note that at the opposite east-west margins of the whole area (i.e. Travale-Radicondoli and Monteverdi) a vaporstatic pressure distribution of about 7 MPa was initially found in the deep undrained layers.

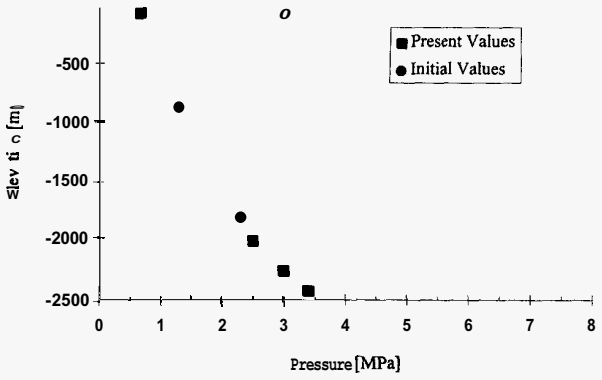

Figure 9. Reservoir pressure vs. depth in the Valle Secolo zone.

The temperature and pressure distribution shows that the geothermal system is steam-dominated everywhere with a superheating of about 50°C in the deep layers.
The liquid phase is present only at the southern boundary where the meteoric waters seep into the reservoir top through the permeable outcrops.
Thus, the Travale-Radicondoli field, previously considered an independent geothermal field, is in fact the eastern margin of a wide and homogeneous geothermal area which includes the Larderello field.

4. CONCLUSIONS

The deep exploration programs at the borders of the area under exploitation identified fractured levels at depths ranging from 2500 m to 4000 m, with reservoir pressures up to 7 MPa and temperatures ranging from 300 to 350°C.

The fluid tapped by the deep wells drilled inside the areas under exploitation made it possible to increase output, offsetting the decline of the wells already in production.
The fluid found in the marginal zones will be utilized in additional power-plants under construction or in the planning stages.
Larderello and Travale-Radicondoli fields, initially considered separate when the wells reached only the reservoir top, turned out to belong to the same geothermal system when drilling was extended to 3-4 km depth.
According to a rough estimate, the potentially productive area has thus been expanded from 200 to 400 km^2 and the reservoir volume has increased from 200 km' to 1000 km'.
Since the whole system is mostly steam dominated with a degree of superheating of some 50°C, an enormous potential exists for secondary heat recovery through water injection.

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