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RECENT DEEP EXPLORATION RESULTS AT THE MARGINS OF THE LARDERELLO TRAVALE GEOTHERMAL SYSTEM

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ABSTRACT

Within the framework of research in the marginal areas of the Larderello–Travale geothermal system, several exploration wells have disclosed an extension of the deep reservoir even below zones of medium or low superficial thermal anomaly.
NE of the Larderello field, Sesta_6bis well crossed a known low temperature (100°C) CO_2 saturated carbonate aquifer, but, at greater depth, in the phyllitic metamorphic basement, a steam reservoir has been discovered at 2400–2800 m. The temperature and pressure are similar to those recorded at the Travale field (300°C and 70 bar).
Two other wells have been drilled in the area south of Travale characterized by large outcrops of permeable carbonate rocks. These constitute the shallow reservoir, bearing fresh meteoric waters, which mask any deeper thermal information. The well Travale Sud_1 crossed several steam productive layers between 2280 and 2890 m in thermometamorphic and granitic rocks. The reservoir temperature and pressure are 300°C and 70 bar. The well Montieri_4 crossed a thick carbonate sequence and then a granitic body from 2000 m to the bottom hole (3700 m), with rather low permeability but with the same temperature and pressure as the deep Travale reservoir. Surprisingly, injection and acidification tests have improved the hydraulic connection with the reservoir.
All the above-mentioned exploration wells have proved to be productive and confirmed the extension of the deep steam-dominated reservoir in marginal areas where the superficial thermal gradient is low.
The deep reservoir is located at a depth of about 3 km inside the metamorphic basement and the granitic body. On the basis of these results, the exploration has been extended and specific development projects have been planned.

1. INTRODUCTION

The deep exploration in the Larderello and Travale geothermal fields revealed the presence of a deeper reservoir at depths ranging from 3000 to 4000 m with a pressure of up to 70 bar and temperatures between 300 and 350 °C (Barelli et al., 1995).
Only one great deep thermal anomaly has been found under the shallow carbonate reservoir and is common to both the Travale and the Larderello geothermal fields (Fig. 1).
The deep reservoir is located inside the metamorphic rocks of the basement, made up of phyllites, micaschists and gneiss.
The metamorphic basement and the overlying calcareous-anhydrite formations constitute a structural high (Bertini et al., 1994) which, although characterized by high density rocks (about 2.7 g/cm^3), falls into a wide negative gravimetric anomaly (Fig.2).
To reproduce this anomaly, 2D gravimetric models require the presence of low density bodies (2.45 g/cm^3), interpreted as granite intrusions at depths ranging between 8 and 12 km (Baldi et al., 1995). This value of density seems to suggest that the granite bodies have temperatures of 800°C and are partially molten (Bottinga and Weill, 1970).
Also of geothermal interest is the seismic marker "K" (Batini and Nicolich, 1984) found at depths between 3 and 7 km and showing a clear correlation with the above-mentioned minimum gravimetric anomaly (see Fig. 2). This marker may indicate a zone of brittle/ductile transition of the rheologic behavior of the rocks because of the temperature (Cameli et al., 1993). Some deep thermal data provide evidence that temperatures of 400–450°C, with lithostatic pressure of about 1 kbar may characterize this marker.
Although characterized by permeable shallow structures and therefore by cold or moderately hot aquifers, the northern and eastern margins of the Larderello-Travale geothermal system are within a great deep thermal anomaly, which may be correlated to the negative gravimetric anomaly and to the structure of the deep seismic marker (K).
The two new areas of Sesta and Chiusdino-Montieri were therefore chosen and over the last five years three wells (Sesta_6bis; Travale Sud_1; and Montieri_4) have been drilled with the aim of extending exploration to the eastern margin of the whole Larderello-Travale geothermal area.
The Sesta area is situated at the eastern border of the Larderello field where the shallow geothermal reservoir is characterized by a moderately hot aquifer (approx. 120°C) with a gas cap.
The Chiusdino–Montieri area, to the south of the Travale field, is characterized by wide outcrops of carbonate-anhydrite rocks, which, on account of their high permeability, may locally represent areas of natural recharging of the geothermal reservoir.

2. DRILLING RESULTS

The location of the exploratory wells must also take into account environmental aspects and acceptability by local administration and inhabitants (we are working in Tuscany).
Preference is given to areas where exploitation is possible and new geothermoelectric power plants can be installed.

2.1 Well Sesta_6bis

The Sesta_6bis well (total depth 3921 m) is located in the western neogenic margin of Radicondoli–Chiusdino, representing the most evident tectonic structure east of the geothermal field of Larderello. This structure is bordered by a system of NW–SE trending faults which also crosses the geothermal field of Travale (Lazzarotto and Mazzanti, 1978).
Preliminary detailed geophysical surveys allowed an accurate location of the well so as to avoid crossing the gas accumulation on top of the shallow geothermal reservoir.
From a geological viewpoint, the Sesta_6bis well crossed 250 m of neogenic sediments and 310 m of flysch facies formations.
At the depth of 560 m, and consistent with the interpretation of geophysical data, the well crossed the tectonic contact

between the cover formations and the underlying Triassic carbonate-anhydrite formations. These are intercalated with phyllites and Triassic-Paleozoic quartzite and constitute the sequence of the Tectonic Wedges (Pandeli et al., 1991).
The well was drilled through these formations, about 1330 m thick, without encountering any significant permeable levels, but a total loss of circulation (TLC) occurred at the depth of 2363 m. A stratigraphic reconstruction below the TLC was performed on the basis of mechanical coring and geophysical logs.
The underlying metamorphic formations met at the depth of 1890 m are made of chlorite–graphitic phyllites with intercalation of limestone (2745-2860 m of depth) and paragneiss. High temperature hornfels are located at bottom hole (3921 m).
The direct contact between phyllites and paragneiss with the absence of micashists is due to a low-angle normal fault towards E-NE (Fig. 3).
Thermometamorphic biotite (400°C) was observed above the fracture at 2363 m, where TLC occurred, but was found to be absent in the underlying cores. The biotite might have resulted from a previous circulation of magmatic fluids, uprising through hydro-fractured systems (Gianelli and Bertini 1993; Gianelli and Ruggeri 1999).
The presence of a subsequent hydrothermal phase, with temperatures higher than 300°C, is indicated by epidote deposits.
The thermal profile of the well (Fig. 4) is characterized by a constant gradient of around 120°C/km down to 2363 m.
Temperatures in the final part of the well were measured according to the fluid temperature recorded at the wellhead during production tests.
The fracture at 2363 m is characterized by injectivity of 5-6 m^3/h/bar and steam pressure of about 50 bar.
Other fractures are present at 3120 m, 3375 m and in the section 3600-3720 m, with injectivity of about 2.5 m^3/h/bar, temperatures of 300°C and steam pressure of about 70 bar.
Extensive production tests have shown that this well may produce about 35 t/h of dry steam with a non-condensable gas content of about 8.5% by weight.

2.2 Well Travale Sud _1

The well Travale Sud_1 (total depth 2897 m) is located approximately 4 Km SE of the Travale exploited area, where wide outcrops of the carbonate-anhydrite formations hosting a cold meteoric aquifer are present.
The well cut these formations, with the thickness of 455 m, and underlying sequence of the Tectonic Wedges, down to 1630 m, made up of Paleozoic phyllites with intercalation of anhydrite. From 1630 m down to a TLC, found at a depth of 2228 m, the metamorphic basement is present. This consists of phyllites, thermometamorphic and carbonate metasomatic rocks (Skarn) with thin veins of granite composition.
The stratigraphic sequence from 2228 m down to bottom hole has been reconstructed by means of mechanical coring, geophysical logs and vertical seismic profile (VSP) which, at a depth of 2400 m, allowed the identification of the top of the thermometamorphic aureole (Andalusite). Geophysical logs (Gamma Ray and VSP) also evidenced an underlying granite intrusion at a depth of 2680 m.
Except for the shallow part, which is affected by the circulation of meteoric waters, the temperature profile of this well is characterized by a conductive gradient between 120 and 150°C/km to the TLC at 2228 m where a temperature of about 300°C has been recorded (see Fig. 4).
Well testing showed that the main productive fracture is at 2420 m with injectivity of 5 m^3/h/bar and reservoir pressure of about 70 bar.
Preliminary production tests have indicated that the Travale Sud_1 well could produce approx. 50 t/h of steam with a wellhead pressure of 30 bar.

2.3 Well Montieri_4.

The Montieri_4 well (total depth 3721 m) is also located near the wide outcrops of the cold shallow reservoir rocks.
After 100 m of shale of the Flysch Nappe the well was drilled through a 1000 m thick sequence of the Tectonic Wedges, consisting of dolomitic limestone and Triassic anhydrite.
The underlying metamorphic basement consists of chlorite–graphite phyllites, presenting thermometamorfic biotite from a depth of approximately 1300 m, and horn fells from about 1900 m.
A granite body, which is highly hydrothermalised in the first 1000 m with formations of chlorite and epidote, extended to a depth of 2000 m.
The thermal profile (see Fig.4) in the first 1000 m, corresponding to the sequence of the Tectonic Wedges, shows a low geothermal gradient consistent with the presence of gypsum and calcite deposits in the fractures, providing evidence of low temperature fluid circulation.
The geothermal gradient in the basement increases up to around 150°C/km and remains unchanged as it crosses the thermometamorphic rocks (horn fells) and the underlying granite intrusion.
Between 2200 and 2740 m the geothermal gradient decreases due to permeability in the granite, indicated by several occurrences of circulation loss and the spread hydrothermal alteration. Fluid inclusions in the chlorite mineralisations provide evidence for the circulation of low salinity hydrothermal fluids (5wt% NaCl) at the temperature of 310–370°C.
Further, but modest, loss of circulation is present down to the depth of 3530 m, where a TLC has occurred.
The main fractures, which were tested during drilling, had initially low of injectivity (0.2-0.7 m^3/h/bar). Several acidification tests (mixtures of HF-HCl) were therefore performed, resulting in a large increase in injectivity. In particular, the fracture at 2880 m is characterized by an injectivity of 5 m^3/h/bar, a reservoir pressure of about 60 bar and temperature of 300°C.
A production test was carried out for some days, and a steam flow rate of about 50 t/h was measured. Unfortunately, the well collapsed close to the production horizons and a repair operation is being planned.

3. CONCLUSIONS

Larderello and Travale have been chosen as exploration areas because of their structure and geothermal features, and also on the basis of environmental evaluations and acceptability, as well as to guarantee the feasibility of the development projects.
The exploration wells Sesta_6bis, Travale Sud_1 and Montieri_4 have confirmed the presence of deep reservoirs with temperatures of 300–330°C and pressures of 50-70 bar.
In particular, the well Sesta_6bis, although drilled where reservoir with low to medium temperatures is found at

shallow depths, has verified the continuity of the deep reservoir between the geothermal fields of Larderello and Travale. The main fracture of the well Sesta_6bis (2370 m) is probably related to a system of hydrofractures of magmatic origin. Therefore, this aquifer probably represents an up-flow of the underlying geothermal reservoir, at a depth of approximately 3100 m.

Both the wells Travale Sud_1 and Montieri_4 have confirmed the presence of deep reservoirs at the southeastern margin of the Travale field, underneath the carbonate-anhydride outcrops containing cold meteoric waters. This provides new opportunities for further exploration south of the Larderello-Travale geothermal field.

The reservoir encountered by the well Travale Sud_1 is found inside a wide contact metamorphic aureole and inside the upper part of a granite intrusion.

The deep reservoir of Montieri_4 is characterized by fractures widely distributed in a granite intrusion. Pressure and temperature are similar to those recorded in the other wells. Acidification operations have considerably increased the permeability of these fractures.

The presence of geothermal reservoirs inside granite intrusions is the main knowledge gained by the wells Montieri_4 and Travale Sud_1.

The positive results of these exploratory wells have allowed the implementation of development projects. Directional wells will be drilled in order to minimize the drilling sites, and, consequently, the environmental impact. Two units, 20 MW each, will be installed in the area and supplied additional wells.

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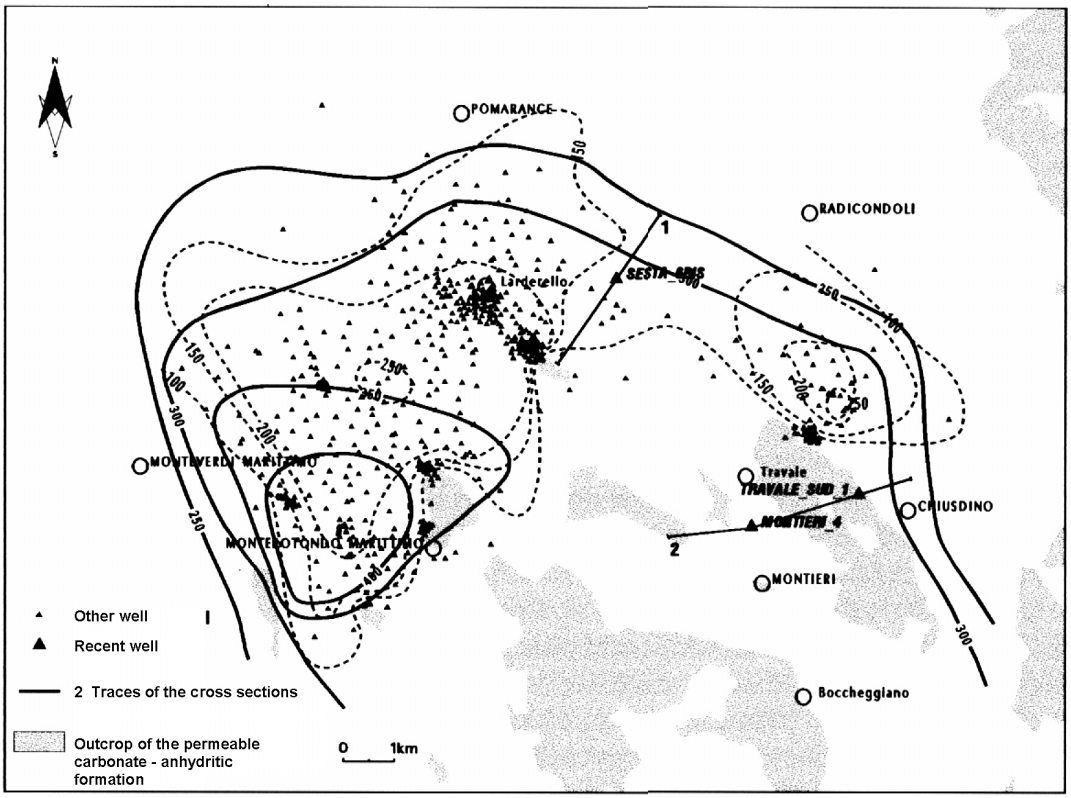

Fig. 1 - Temperature distribution at the reservoir top (dashed line) and at depth of 3000 m b.s.l. (continous line).

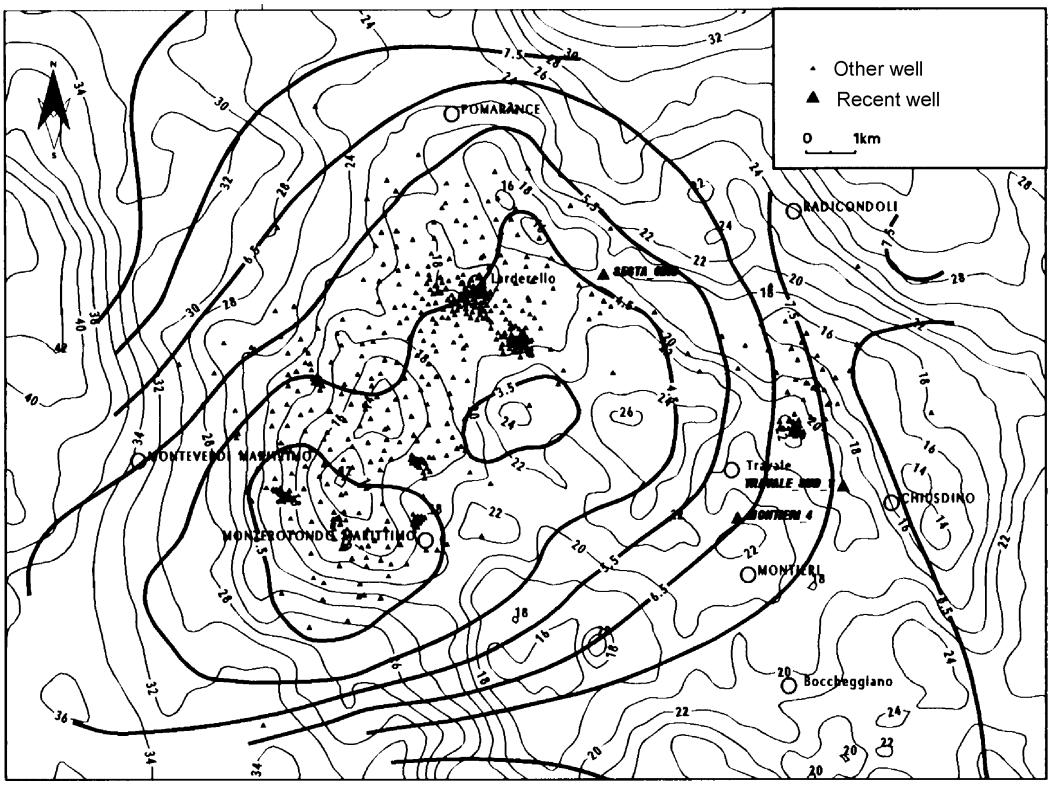

Fig. 2 - Map of the gravimetric Bouguer anomaly (fine line in mgal) and of the top of the seismic marker "K" (bold line in Km b.s.l.).

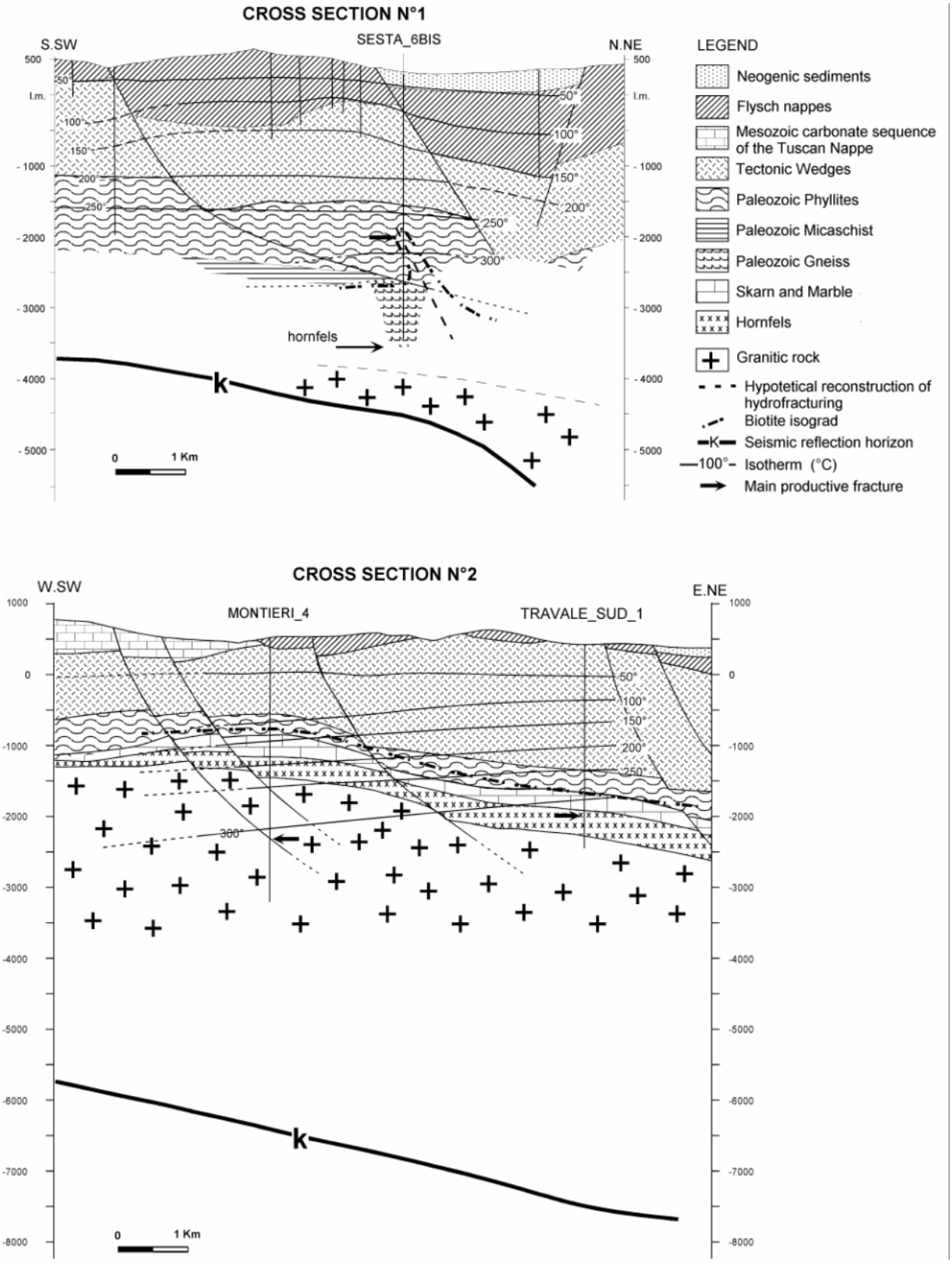

Fig. 3 Schematic geological cross sections through SESTA (N° 1) and MONTIERI - CHIUSDINO (N° 2) exploration areas. (Traces on fig. 1)

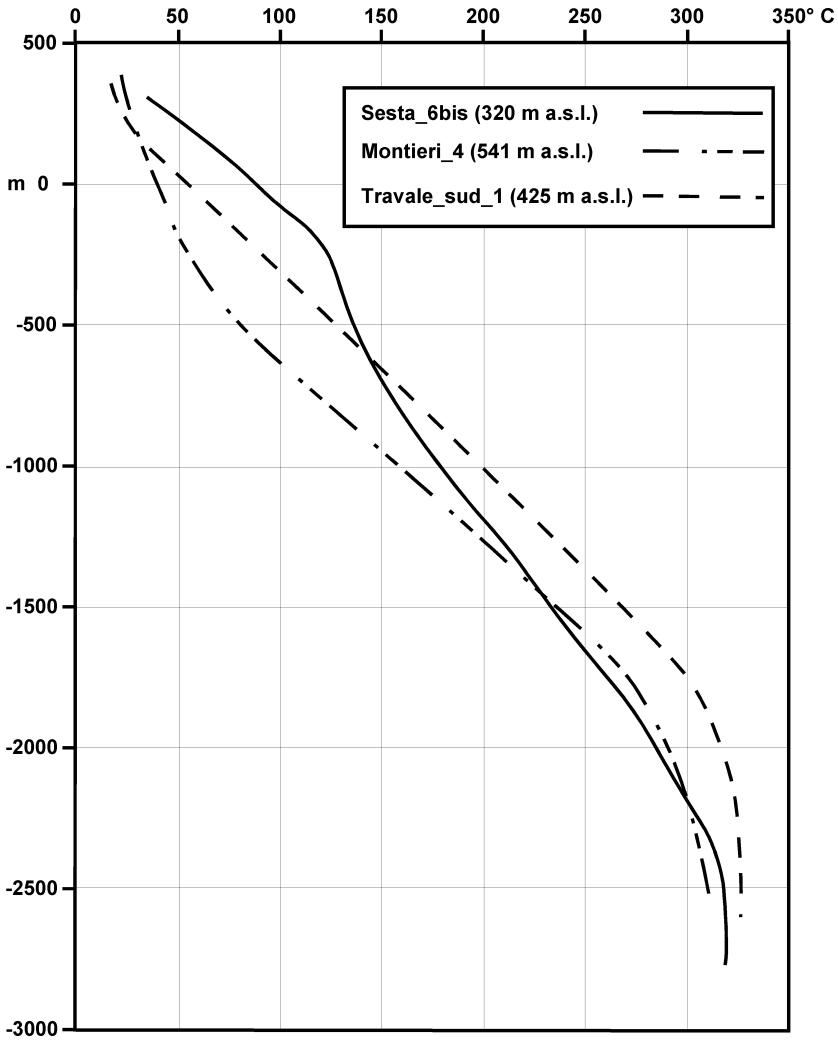

Fig. 4 Temperature versus depth in the exploration geothermal wells.