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# An Update of the Larderello-Travale/Radicondoli Deep Geothermal System

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## ABSTRACT

Within the framework of research in the marginal areas of the Larderello–Travale/Radicondoli geothermal system, several exploration wells have revealed that the deep reservoir extends even below zones of medium or low shallow thermal anomaly. North-east of the Larderello field, the shallow wells crossed a known low-temperature (100°C) $CO_2$ saturated carbonate aquifer. At greater depth, in the phyllitic metamorphic basement, a steam reservoir has been discovered at depths of about 3000 m. The temperature and pressure are around 300°C and 7 MPa, respectively (Cappetti et al., 1985; Cappetti and Stefani, 1994; Cappetti et al., 1995).

Other exploratory wells, drilled in the area south of Travale/Radicondoli, discovered the same deep reservoir, although large outcrops of permeable and cold carbonate rocks are present.

On the basis of these positive results, specific development projects have been implemented in these two areas, leading to the installation of new power plants for an additional capacity of 80 $MW_e$ (Cappetti et al., 2000).

Larderello and Travale/Radicondoli deep reservoirs have the same temperature (300-350°C) and pressure (4-7 MPa): they belong to the same geothermal system. The surface extension of this deep field is about 400 $km^2$. A new extensive deep drilling exploration program has been launched in 2004.

## 1. INTRODUCTION

The high enthalpy superheated steam reservoirs under commercial exploitatio/development in Tuscany are located in the Larderello and Travale/Radicondoli areas (Barelli et al., 1995, a and b; Barelli et al., 2000). These two areas are located approximately 15 km apart, and both exhibit a similar geological structure: a shallow carbonate reservoir, exploited for many years, and a deeper reservoir within the metamorphic basement, discovered during the last 20 years.

### 1.1 Larderello area

The first geothermal well has been drilled in 1832, but the productive shallow carbonate reservoir of the Tuscan Nappe was reached in 1926. Intensive exploitation had covered an area of approximately 180 $km^2$ by the end of the 70s, when the limits of the shallow productive reservoir were reached. These limits are shown in Figure 1, highlighted by the 200°C isotherm at the top of the reservoir (less than 1,000 m). The pressure in this shallow reservoir has decreased as a consequence of long-term commercial development and is now in the range 2.5-0.7 MPa, with a few shallow areas with lower values.

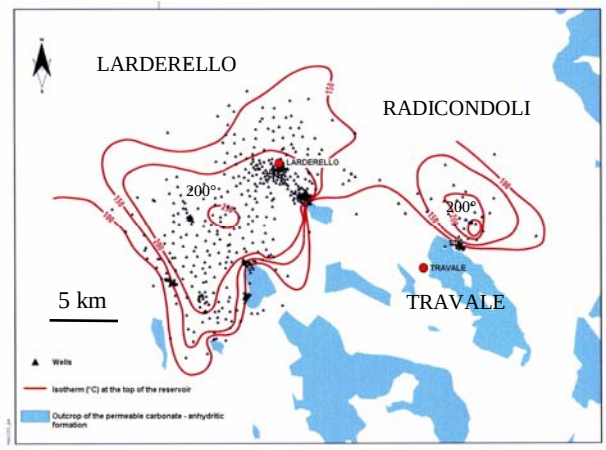


**Figure 1: Temperature distribution at the top of the shallow reservoirs (approx. 1,000 m): the outcrops of the reservoir formation are highlighted in blue**

A deep exploration program was begun in the 1980s and proved the existence of deep productive layers inside the metamorphic basement underlying the carbonate-evaporite reservoir. The results of this program were very encouraging and have led to the implementation of new development projects.

### 1.2 Travale/Radicondoli area

Exploration of Travale/Radicondoli area began in 1930, near the natural manifestations, but its industrial development effectively only started in the 50s. Two major shallow carbonate evaporite reservoirs have been identified:

(A) Horst: at 600-800 m depth, with a very high production since the 70s, with 6 MPa and 270°C. Production from this area has now roughly stabilized around 40 kg/s, with a pressure of 1.9 MPa.

(B) Graben: in the 80s exploration was directed at the intermediate zone, at a depth of 1300-2500 m; a productive area has been identified and exploited. The pressure dropped from the initial 6 MPa to 3.9 MPa, while the flow rate decreased to the stabilized value of 30 kg/s.

The extension of the shallow system is shown in Figure 1, bounded by the 200°C isotherm.

A deep exploration program was also launched inside the metamorphic basement in this area, with similar positive results as in Larderello. The deep system is extending also into areas with outcrops of the carbonate reservoir rocks (i.e. under the inflow of the cold meteoric water) but where impermeable layers within the metamorphic rocks separate the shallow cold circulation from the deep reservoir.

## 2. THE DEEP GEOTHERMAL SYSTEM

The Larderello – Travale/Radicondoli deep reservoir has the same temperature (300-350°C) and pressure (4-7 MPa) throughout its areal extension. It is an immense deep geothermal system covering about 400 km$^2$ under the shallow carbonate reservoirs and also under zones where the thermal gradient near the surface was very low, with no evidence of springs or gas manifestations. Figure 2 shows the isotherms at 3,000 m depth, proving the deep connection between the Larderello and Travale/Radicondoli areas.

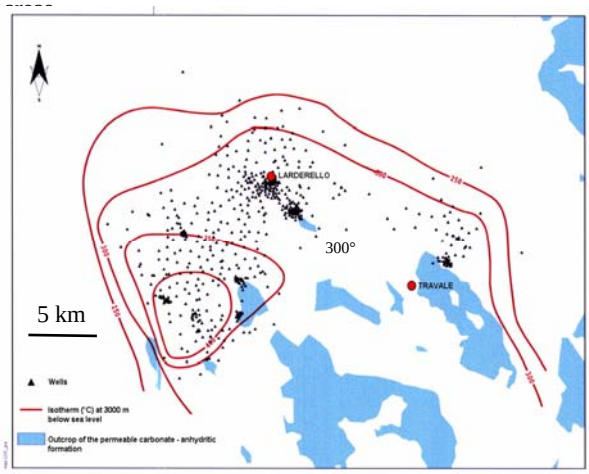


**Figure 2: Larderello-Travale/Radicondoli area: temperature distribution at the depth of 3,000 m**

This deep reservoir is steam-dominated throughout, with about 50° of superheating. It is located in fractured zones inside the metamorphic paleozoic basement in correspondence of a "structural high" of this formations (phyllites, micaschists and gneiss groups). It is bounded by the 300°C isotherm, as shown in Figure 2.

The top of the metamorphic units (see Figure 3) exhibits a NW-SE structural high, uncropping in the Larderello region. The higher structure is located in the Montieri-Chiusdino area, and it is probably related to the shallow great granitic intrusion.

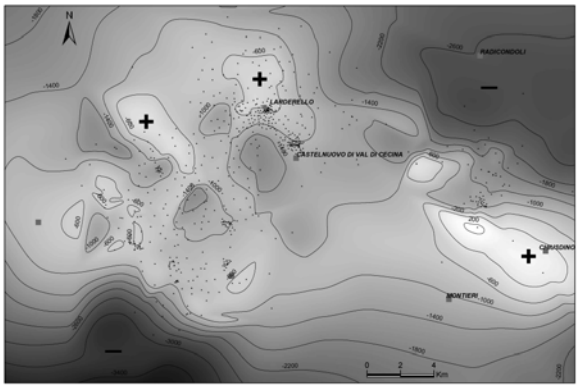


**Figure 3: Top of the metamorphic basement (m.a.s.l.)**

Recently, the deep wells discovered the high permeable productive horizons in correspondence of the metamorphic contact rocks and less frequently inside of the granitic intrusions (see Figure 4 in the last page of present paper).

## 3. MAIN DEEP DRILLING RESULTS

Over the last ten years, geothermal exploitation in the Larderello–Travale/Radicondoli fields has been implemented in many areas by means of deep drilling. Some of these areas were previously investigated by geophysical surveys and exploration wells. A map of the area with the location of some deep wells is shown in Figure 5.

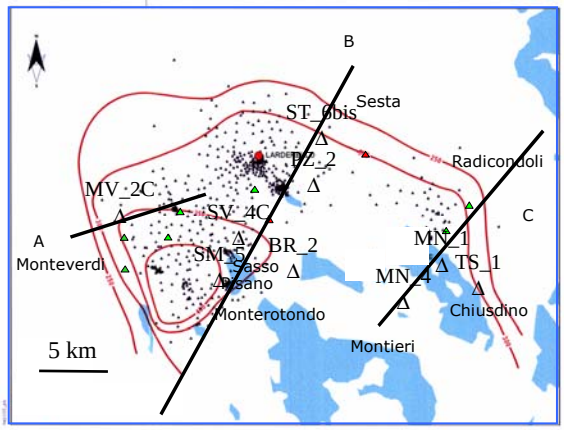


**Figure 5: Map of the Larderello-Travale/Radicondoli area, showing the location of the geological cross-sections A, B and C reported in Figure 4. The analyzed wells are represented in the figure by triangles.**

For some selected deep wells in each area we will present the following data:

- stratigraphic sequence,
- seismic targets,
- the location of productive fractures.

The two seismic reflectors, H and K, represent the most important deep seismic horizons detected by the 3D and 2D surveys. 'H' can be interpreted as the metamorphic contact aureola of the old (2-3 my) granitic intrusion. It normally coincides with the deep reservoir. The 'K' horizon has never been reached in this area: it could be interpreted as a metamorphic contact aureola of the Quaternary granitic intrusion.

### 3.1 Monteverdi

One of the study areas is Monteverdi (see Section A of Figure 4), located on the western border of the Larderello geothermal field. A total of 23 wells, mostly directional, were drilled in this area by the end of the last century. These wells crossed a deep (>3000 m) geothermal reservoir with temperatures of more than 300°C and steam pressure of about 7 MPa. The target for MV_2C vertical well was also defined on the basis of the new information from the 3D seismic survey. A seismic horizon (H) was identified at about 3500 m depth, characterized by high frequency and amplitude; this horizon had never been reached in previous drillings.

MV_2C well reached 3944 m depth and crossed a productive layer with about 11 kg/s of steam. The productive fractures are located near the re-crystallized limestone (3550 – 3600 m) inside the metamorphic contact of siliceous rocks with thin granitic intrusions (Figure 6).

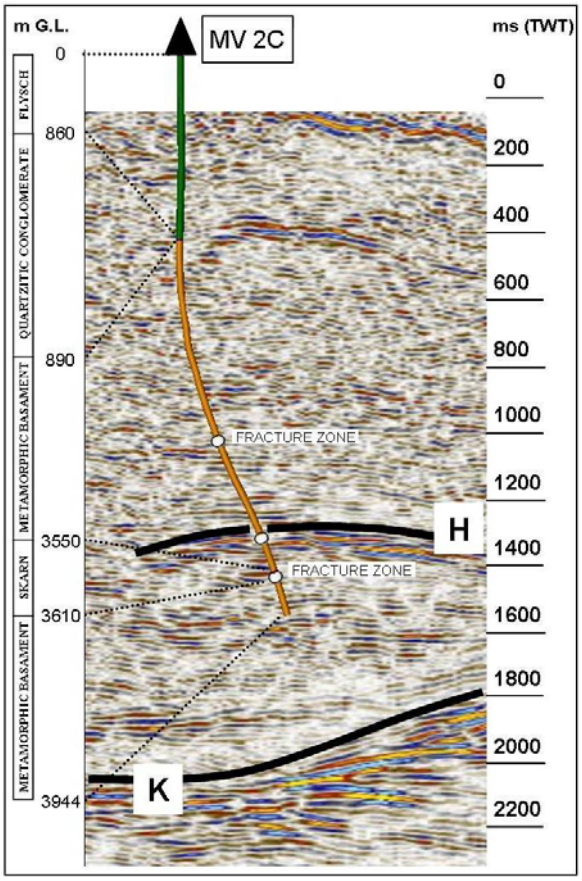


**Figure 6: well MV_2C**

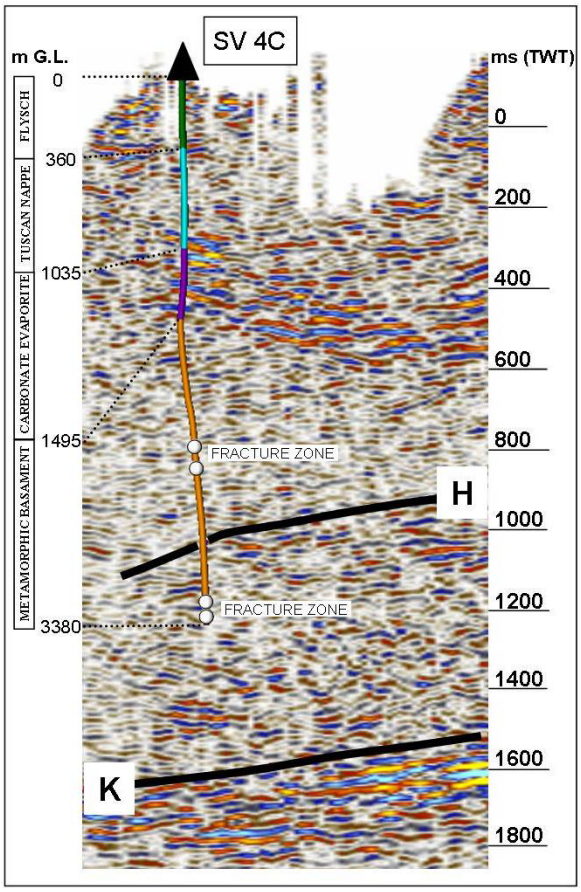


**Figure 7: well SV_4C**

### 3.2 Sasso Pisano

A similar approach was adopted during the 3D seismic survey of the Sasso Pisano area, located in the central part of the Larderello field (see Section B of Figure 4). A new deep target was detected on the SV_4 well site. It is represented by a strong seismic signature at about 3300 m depth. Four deep wells have been drilled from the same pad. The last one, SV_4C, reached 3338 m depth. A new productive zone, with temperatures of about 350°C and pressure of 5.5 MPa, has been discovered from 3100 m to bottom-hole in metamorphic contact of siliceous rocks. Maximum flow rate was 30 kg/s.

The characteristics of well SV_4C are shown in Figure 7.

The same 3D seismic survey was also adopted for BR_2 deep well (about 2 km south-east of well SV_4C). It was productive from some fractures inside the metamorphic basement, characterized by temperature more than 300°C and pressure of about 5 MPa.

### 3.3 Monterotondo

The new exploratory wells SM_5 (2102 m) and SM_5A (2258 m), were drilled in the Monterondo area (South of Sasso Pisano). Temperatures and pressures of more than 300°C and 2.5 MPa are present in this area at 1000 m depth, inside the metamorphic basement. At 2000 m depth, pressure is about 4 MPa.

A maximum flow rate of about 17 kg/s was found in the wide fracture zone (1400 – 2200 m) in the metamorphic basement (see Section B of Figure 4).

### 3.4 Sesta

Deep exploration in the Sesta area (see Section B of Figure 4) began in 1997 with well ST_6BIS (3921 m depth), followed by four additional deep wells in the same area.

A new 20 MW unit has been installed. With the drilling of the exploratory well of PZ_2 (4379 m), located in the south western part of the Sesta area, it was verified the extension of the deep reservoir toward SW. The characteristics of PZ_2 well are shown in Figure 8.

### 3.5 Montieri-Chiusdino

After the success of TS_1 exploration well (2897 m depth) in the Montieri – Chiusdino area (see Section C of Figure 4), drilling continued with five productive wells. Well MN_4 is also shown in section C of Figure 4: this well crossed a thick part of the granitic intrusion, with the productive layer at 2600-2800 m, and has a flow rate of 15 kg/s.

In this area only a few wells crossed a granitic intrusion (3 my). The main productive layers were found from 2200 to 2600 m depth in the metamorphic contact of carbonate rocks, near the top of the granitic intrusions.

Temperature >300C° and pressure of 7 MPa have been measured. These are the same geothermal characteristics of the deep reservoir (3000 – 4000 m) of the surrounding area of Radicondoli. In Montieri area, well productivity is high. MN_1 set the record in Italy for high steam production, with an initial value of 50 kg/s. The well characteristics are shown in Figure 9.

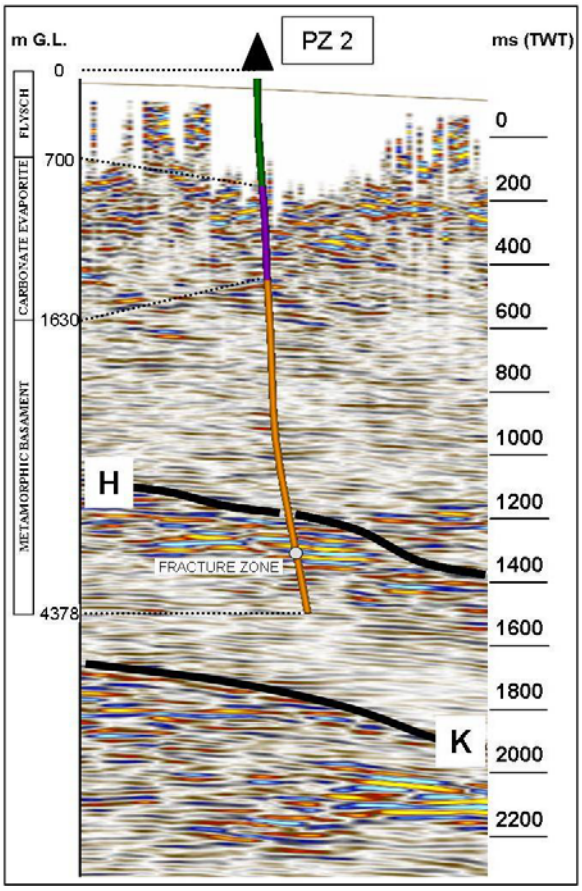


**Figure 8: well PZ_2**

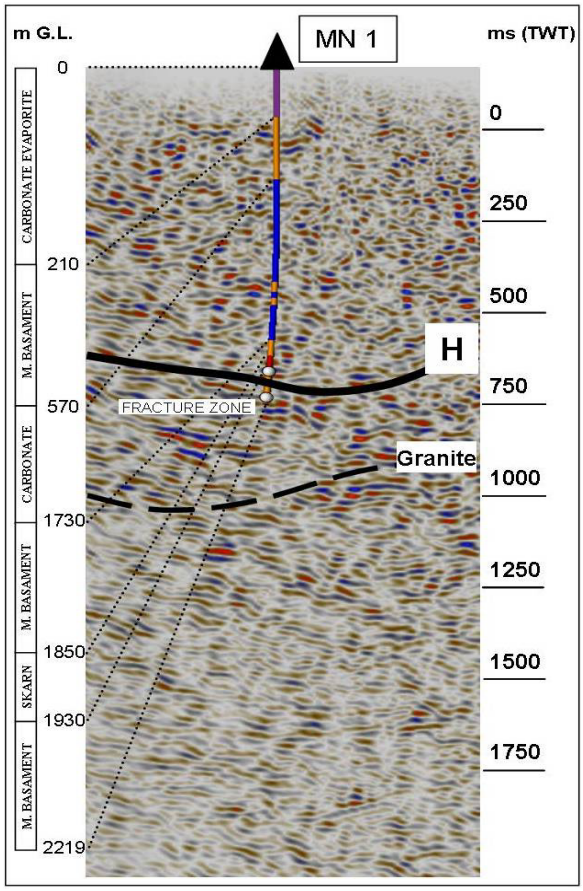


**Figure 9: well MN_1**

The double drilling of MN_1 and MN_1A as twin productive wells led to a total production of about 70 kg/s of steam.

The successful results of deep drilling in this area led to the installation of two new units (20 $MW_e$ and 40 $MW_e$).

## 4. CONCLUSIONS

The deep exploration wells have allowed us to verify the existence of permeable horizons inside the metamorphic basement (2000 – 3500 m), with high productivity and temperatures and pressures of about 300-350°C and 4-7 MPa.

Based on the temperature distribution at 3000 m depth, it is clear that the Larderello and Travale/Radicondoli fields, which were considered separate at the level of the shallow carbonate reservoir, actually belong to the same deep geothermal system. At 3000 m depth the 300°C isotherm contour includes both areas, with a total extension of about 400 $km^2$.

An important role for the identification of deep geothermal targets is played by reflection seismic method. A reliable correlation has been verified between deep seismic markers and fractured/permeable horizons in the metamorphic basement.

A new exploration program has recently been implemented by Enel to verify the possibility of steam production from deep layers located both inside and at the margin of Larderello-Travale/Radicondoli geothermal system (see Figure 10).

This program includes new 3D seismic surveys in the selected areas and drilling of eleven deep exploratory wells.

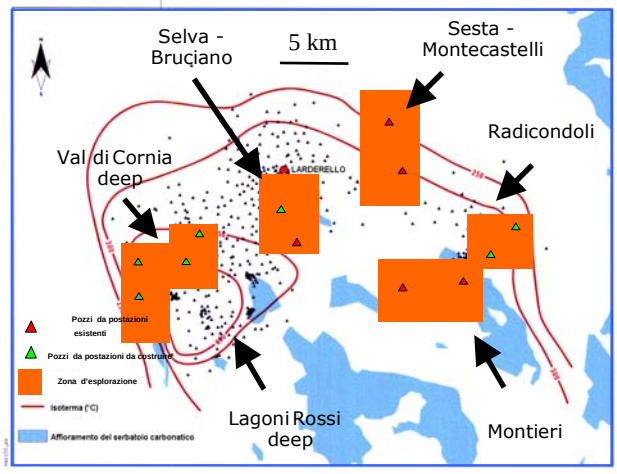


**Figure 10: Map of the Larderello-Travale/Radicondoli area, showing the locations of the five new exploration projects**

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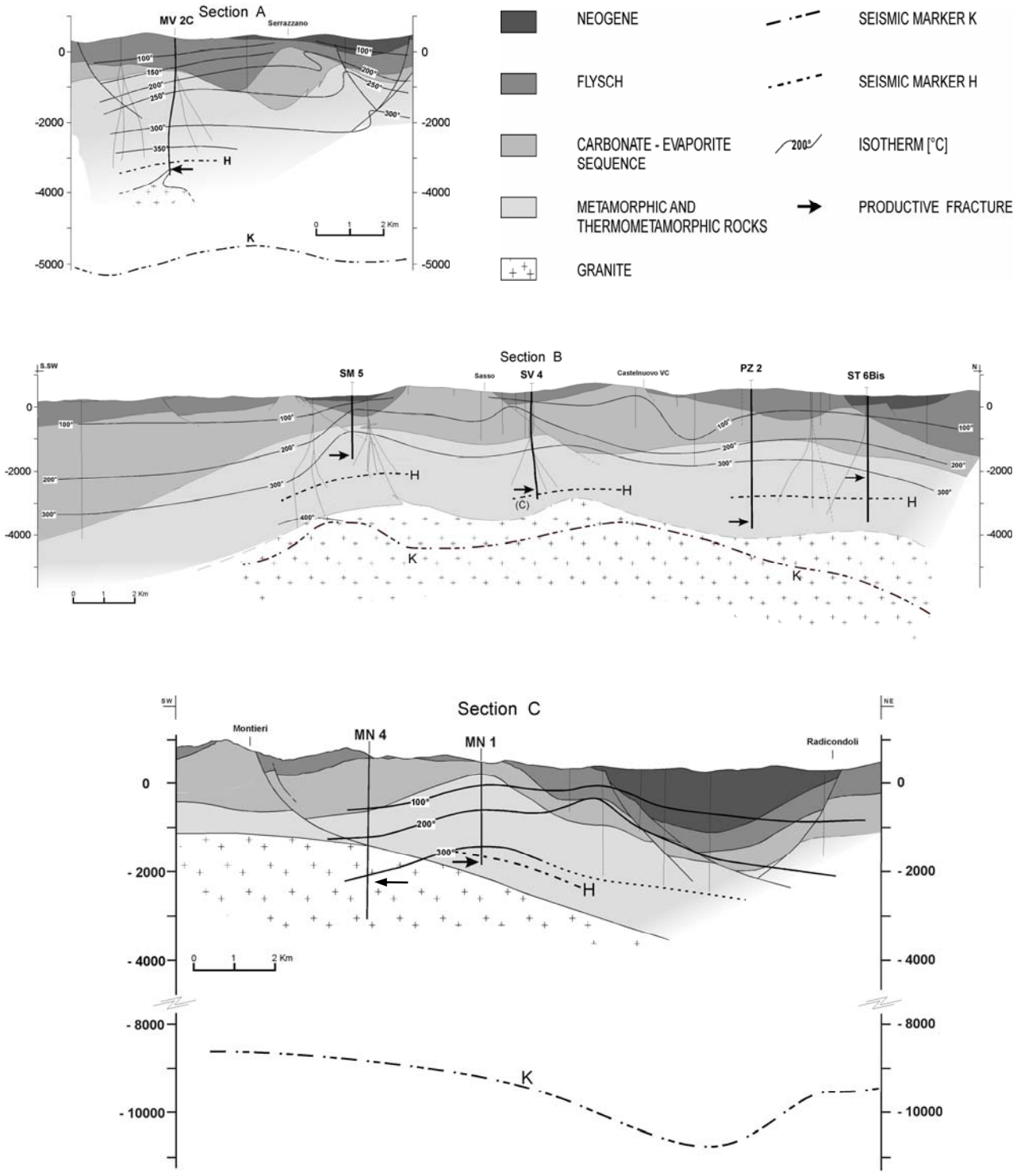


**Figure 4: Geological Cross Sections**