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Data Revision and Upgrading of the Structural Model of the Travale Geothermal Field (Italy)

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ABSTRACT

A big effort of geological data revision and geophysical data reprocessing has been performed for the Travale geothermal system in order to reconstruct an integrated and upgraded structural model of the field.

Stratigraphical data of more than 90 wells have been reanalyzed in order to homogenize the geological features and particular attention has been devoted in the study of the fracture systems revealed by surface geology, core analysis and geophysical well logging.

More than 170 km of 2D seismic reflection lines have been reprocessed and reinterpreted in order to obtain a better definition of geological structures and seismic anomalies to be associated to geothermal productive zones.

The use of advanced software aimed to detailed 2-3D modeling has allowed an integrated interpretation of all the reviewed data and the reconstruction of a realistic geological - geothermal model of the Travale field. In particular the shape of granitic intrusion (3 My) has been drawn as well as the contact metamorphims aureole which seems to be the main deep productive horizon. This is often characterized as a continuous and strong seismic reflector, the so-called H horizon, which generally runs in the central sector of the Travale field, at depth of 2000-4000 m above the deepest and well known K horizon. Thanks to the seismic data reprocessing and interpretation, a new structure of the top of the K horizon has been redrawn.

This upgraded conceptual model represents an efficient tool for the individuation of reliable geothermal targets prior to drilling.

1. INTRODUCTION

Over the last 25 years the geothermal resources exploration in Tuscany has been addressed to deeper reservoir (> 2500 m) which is hosted in metamorphic and granitic rocks. In order to reduce the mining risk and to optimize the deep drilling targets detection, an upgraded geological-structural model of the Travale geothermal field has been reconstructed.

To this aim a multidisciplinary approach has been applied. An accurate revision and integrated interpretation of all the geological and geophysical data collected in over 50 years of geothermal activity has been performed.

The Travale geothermal field has been choused as case study because the deep exploration wells in this area have been particularly successfully and exploitation programs have been planned.

The Travale geothermal field is located in the E-SE part of the wide Larderello geothermal system and extends at the western margin of NW-SE tectonic depression of the Anqua – Radicondoli graben (Figure 1).

Up to 2004 year, 93 wells have been drilled and 180 MW of running capacity was installed.

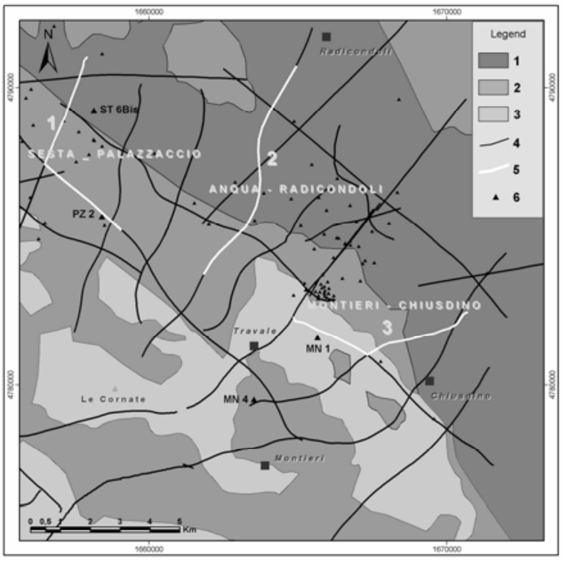

Figure 1: Schematic geological map of the Travale-Radicondoli geothermal area. 1) Neogenic 2) Flysch 3) Carbonate-evaporitic sequence 4) 2D seismic lines 5) Traces of the seismic lines evidenced in Figg. 8-10 6) geothermal wells.

2. GEOLOGICAL AND GEOTHERMAL FEATURES

On the base of geological-geophysical and well data acquired in the past, a preliminary geothermal model of the Travale field was reconstructed, e.g. Barelli et al. (1995). In particular two different reservoirs have been identified:

- a shallow steam dominated reservoir is hosted at 500-1500 m depth in the carbonate Tuscan Nappe Units and evaporitic Tectonic Wedges formations, and is characterized by medium-high permeability, temperature of about 270 °C and reservoir pressure of 6 MPa;

- a deep superheated steam reservoir, in vapor-static equilibrium with the shallow one, is hosted in the metamorphic basement and thermometamorphic rocks, and is characterized by a high anisotropic permeability distribution, temperatures ranging between 300-350 °C and reservoir pressure of 7 MPa.

The productive zones of the deep reservoir are mainly present in contact metamorphic carbonate rocks.

Less productive fractured levels are also present in deeper granitic bodies, where temperatures do not exceed 330°C.

Deep wells did not found productive levels at temperatures higher than 350 °C. Any way the deepest boundary of this reservoir remains an open question, as well as the meaning of the well known "K" seismic horizon. This is a deep strong signature of the whole Larderello-Travale geothermal system, e.g. Batini and Nicolich (1984), Cameli et al. (1993), and is characterized by temperatures of 400-450 °C.

3. DATA REVISION

In order to reconstruct an integrated and upgraded model of the Travale geothermal field, all the available geological and geophysical data have been preliminary selected and collected. An onerous data revision has been performed with aim to homogenize the quality of data acquired in different times and with different procedures.

The complete reviewed dataset has been loaded on an advanced computer system for 3D visualization and modeling.

3.1 Well data

Available geological, thermal and geophysical well data have been reanalyzed.

- *Litostratigraphic* reconstruction of 93 wells has been carried out by means of petrographic analysis of cuttings and cores. It allowed reclassifying the main lithologies of sedimentary and metamorphic formation. In particular 180 *cores* have been reanalyzed also for structural analysis (26 from flysch, 56 from carbonate-evaporitic and 98 from metamorphic formations).

- *Temperature profiles* coming from well temperatures measurements of about 60 wells have been accurately reviewed and verified for a reliable reconstruction of the temperature distribution.

- The main *geophysical logs* usually acquired (GRay, Density, Acoustic) have been reanalyzed for petrophysical characterization and in particular for detecting and characterizing the fractured zones (Figure 2), e.g. Berto et al. (2002), Batini et al. (2002).

- *WSP data* recorded in 14 wells have been reprocessed in order to evaluate an accurate time-depth function and to determine an average P-velocity value of the main geological Units of the area (Figure 3).

3.2 Reflection seismic data

The Travale area has been investigated by 19 2D seismic lines acquired from '70 to 2000 (see Figure 1). In this time laps the acquisition and processing technologies strongly changed. All the lines have been thus reprocessed in order to obtain a homogeneous database for a reliable interpretation. The reprocessing has been focused to preserve quality and amplitudes of the seismic signal content in order to perform seismic attributes analysis, e.g. Mazzotti et al (2002).

A 3D integrated interpretation of these 2D lines has been performed by using of 3D visualization tools and all the available geological and geophysical well data (Figure 4).

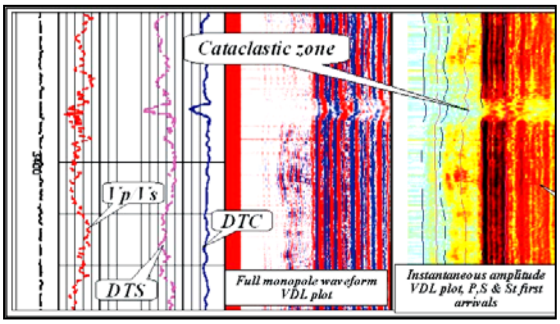

Figure 2: Example of fractured zone analysis from Sonic Log processing (Instantaneous Amplitude).

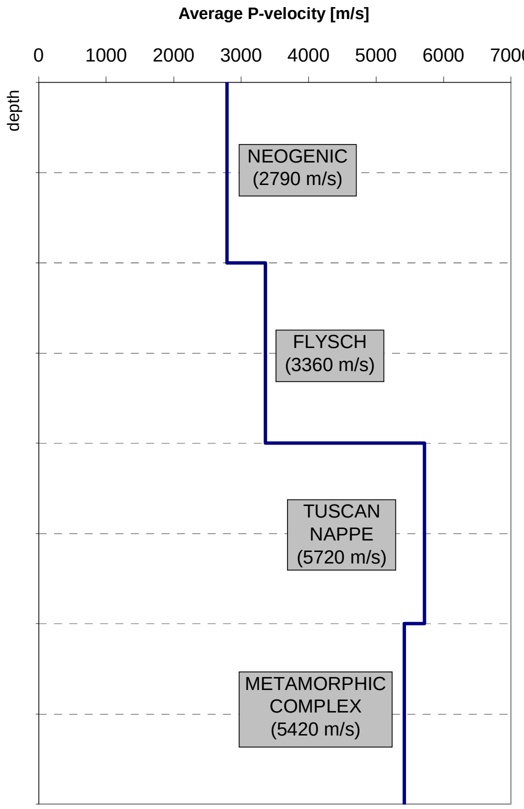

Figure 3: Average P-velocity of the main geological Units from WSP (Well Seismic Profile) analysis.

4. CHARACTERISATION OF FRACTURED ZONES

Detection and analysis of the fractures patterns play an important role in the exploration of deep metamorphic geothermal reservoir. The reservoir permeability depends in fact on fractures density and its distribution.

In this study a tentative to analyze all different information concerning fracture and stress conditions have been pursued.

- The *surface fractures* patterns detected by satellite images and field measurements show a prevalent N110 and N150 trend which is similar to the normal faults direction of the Travale neogenic graben. Secondary N30 and N70 trends are also present. Recent photo-interpretation has evidenced strike-slip structures E-W oriented.

- A *stress field analysis* has been performed from focal mechanisms of earthquakes occurred in the Travale area. This study evidences local zones characterized by apenninic and anti-apenninic strike-slip strains in the framework of the regional tectonic tensional regime, e.g. Albarello et al. (2003).

- *Fractures density analysis* has been carried out in more then 100 not oriented *cores*. Joints are frequently distributed at depth of 1500–2000 m with slope of 30 – 60°, while just few faults are present. These fracture zones correspond to the lower part of the evaporitic formation and to the upper part of the metamorphic basement. Going deeper the fractures density (sub vertical joints) decreases with depth (Figure 5).

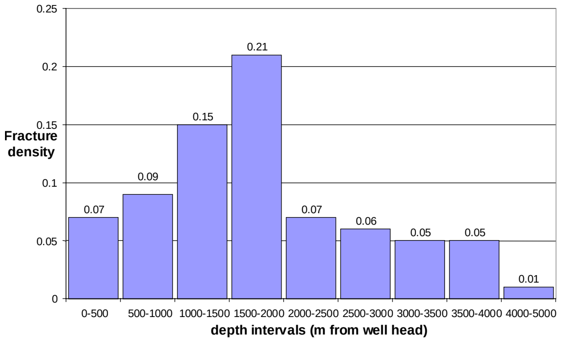

Figure 5: Structural analysis of drilled cores: distribution in depth intervals of fracture density (n° joints-faults/ cm of core length observed)

- *Circumferencial Borehole Image Log* (CBIL) have been acquired for fractures characterization in few and widespread wells. In the NW sector of the Travale basin (Sesta area), CBIL has shown that fracture patterns change with depth: in the shallow part of the metamorphic basement a NW-SE direction with a slope < 40° is prevalent, while in the deepest part sub vertical fractures with E-W direction prevail. In the SE sector (Chiusdino area) prevalent NE-SW and secondary N-S fracture patterns are present. These last are sub vertical and seem to be characteristic of fracture systems in granitic intrusion.

5. THE STRUCTURAL MODEL

The analysis of the available data has allowed a revision and upgrading of the Travale structural model (Figure 6), based essentially on 2D seismic interpretation which has been integrated and constrained by well data. This interpretation, e.g. Fiordelisi et al. (in this volume) has allowed a detailed reconstruction not only of the already known *K horizon* but also of the shallower *H horizon* which is less continuous, but similarly characterized by high amplitude signals. For the structural reconstruction, all the seismic signatures have been converted in depth by using the time/depth function obtained by WSP and velocity data by Sonic logs. The main features of this model are here below summarized.

Granitic rocks crossed by many deep wells can represent the culminations of wide deep batholiths. The tensional tectonic regime of the area caused the forming of neogenic basins and probably the uprising of the intrusions which have age of 2.3 e 3.0 My. These rocks, having temperatures higher than 300 °C, if fractured can host the deep reservoir.

The *H horizon* often corresponds to a thermometamorphic aureole and extends few hundred of meters above the intrusive bodies. For this reason it has been utilized for mapping the top of the granite also in areas where wells are not present or did not reach intrusions (Figure 7). It is also a very interesting geothermal target. Many productive/fractured horizons have been found at its level and are usually associated to mineralized breccia and skarn. Fracture systems can be induced by hydrofracturing, chemical dissolution and decarbonization phenomena. The strong contrast of acoustic impedance which characterizes the H and K horizons can be caused by high fractured levels filled by geothermal fluids with high temperatures and pressure.

The K horizon usually runs below the top of the granitic intrusion and, analogously to the H marker, could be interpreted as a deeper thermometamorphic aureole due to more recent granite intruded at higher depth. This could represent the main heat source of the geothermal system, e.g. Bertini et al. (2004).

The K marker is characterized by many discontinuities which have been interpreted as tensional structures and should exclude that it was characterized by a “ductile” regime. In the western part of the Travale field these discontinuities cannot be correlate with surface tectonic structures, but the prevalent trend NW-SE common to the surface structures and to the K level are conform to the same tensional tectonic regime which is still active from the Neogene and has an important role in the circulation of geothermal fluids.

In the framework of the revised model of the whole Travale area, three zones have been identified with different thermal and structural characteristics: Sesta-Palazzaccio, Anqua-Radicondoli and Montieri - Chiusdino.

5.1 Sesta-Palazzaccio zone

The K and H markers show a quite similar shape with a parallel trend (Figure 8). The K marker is at depth of about 4500 m , while the H marker runs at 3000-3500 m. In this zone the H horizon is in the metamorphic basement and may underline the top of the gneiss. Granitic intrusions have been not found by drillings, but on the base of thermometamorphic deep cores their presence can be hypothesized at depth higher than 4500 m. The productive levels are distributed in a wide interval depth, 2400 - 3900 m, in the metamorphic reservoir and are not correlated to specific lithologies.

5.2 Anqua-Radicondoli zone

The K marker is at depth of 6000-8000 m and becomes gradually deeper going in E-SE direction, where it is characterized by a major discontinuity and minor signal amplitude (Figure 9). The K discontinuities have NW-SE direction which is similar to the surface tectonic structures. The H marker is at depth of 3000-4000 m and its correspondence with thermometamorphic rocks has been verified by many wells. In this zone deep drillings reached granitic intrusion at depth of about 4000 m, few hundreds of meters below the thermometamorphic aureole, and the H horizon is also a marker where the most productive levels are concentrated. Further productive levels have been found also at less depth, always in the metamorphic formations.

5.3 Montieri-Chiusdino zone

The K marker reaches the maximum depth (10 km) and is characterized by weak seismic signal (Figure 10). The top of granitic intrusion has been reconstructed by many wells drilled in this zone and is very shallow (1900-2500 m). The H marker, which is not seismically well defined, could correspond to the top of conctac metamorphic carbonate rocks at depth of 1500-2000 m. The main fractured and productive levels are prevalently concentrated in the neighborhood of the top of the granitic intrusion. In this zone the most deep productive wells (300 t/h) have been drilled.

6. CONCLUSION

The revision and the integrated analysis of the available geological, geophysical and well data allowed a reliable upgrading of the structural model of the Travale geothermal field.

New structural features and geothermal role of the K and H seismic markers have been defined as well as the reconstruction and characterization of granitic intrusions.

Three zones with geothermal reservoirs hosted in different geological-structural environments, have been evidenced and, thanks to this interpretative effort further deep geothermal targets have been identified and proposed for future wells which will be drilled at depth higher than 2500-3000 m where temperatures higher than 270 °C are expected (Figure 11).

In the Travale area at list 9 wells can be foreseen in order to reach the identified targets. Many of these wells could be drilled from existing sites and represent reliable opportunity of development for the deep geothermal system. On the base of the previous experience, the 80% of the wells is expected to be productive and 3D seismic surveys will be performed in order to have a better definition of the targets and a meaningful reduction of the mining risk.

A part of these wells will be carried out in the framework of a new deep exploration program, e.g. Cappetti et al. (in this volume), which foresees the drilling of new 11 explorative wells in the whole Larderello-Travale geothermal system.

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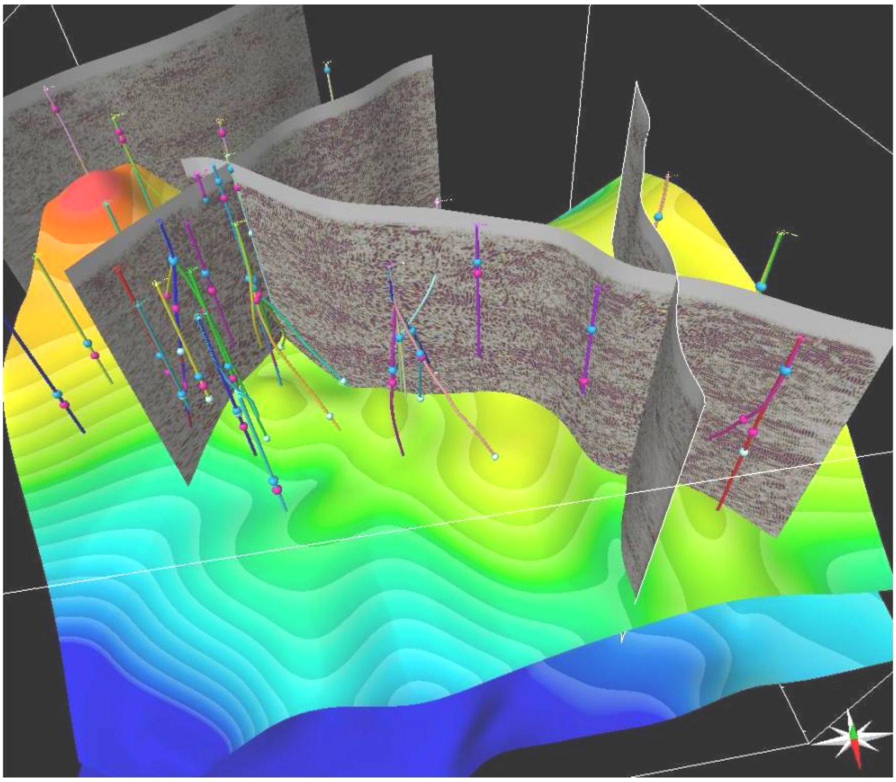

Figure 4: Example of 3D integrated visualization of 2D seismic lines, geological horizons and well profiles with stratigraphical markers

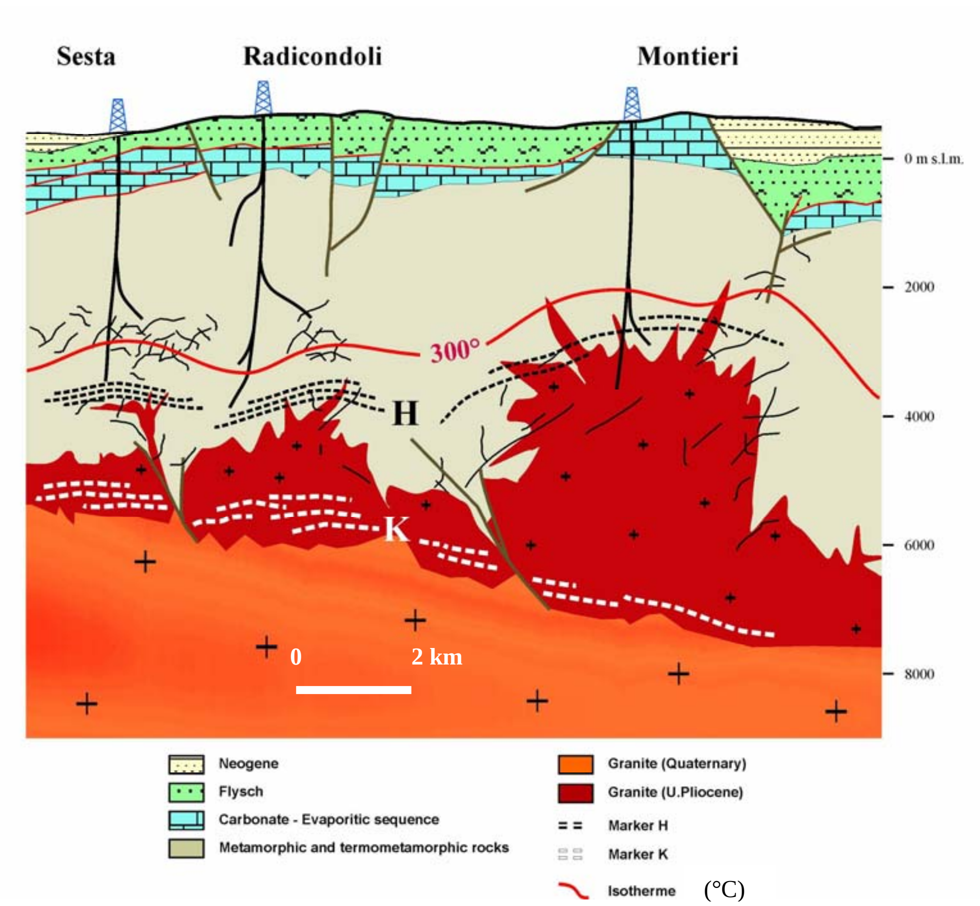

Figure 6: Schematic structural model reconstruction of the Travale geothermal field

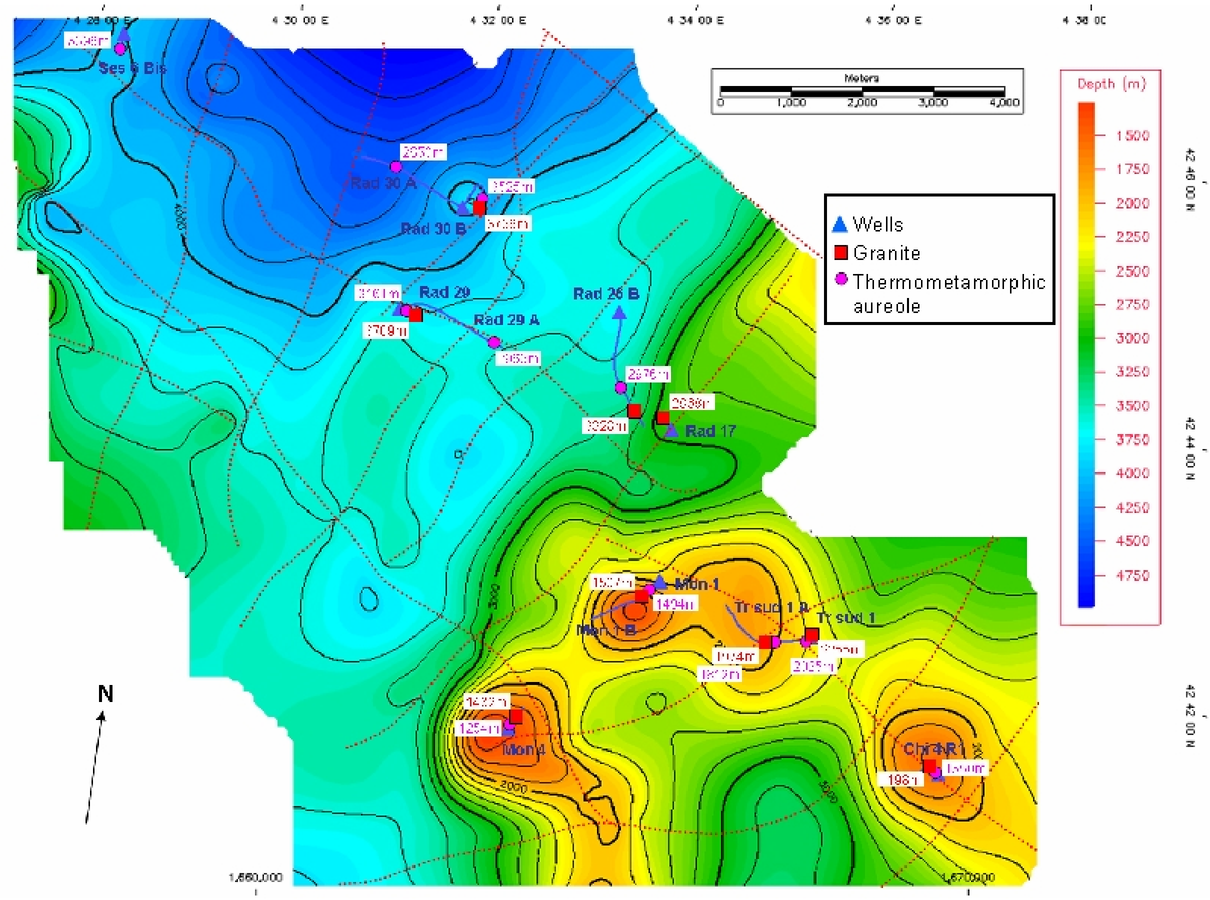

Figure 7: Map of the granite top (a.s.l.) in Travale geothermal field.

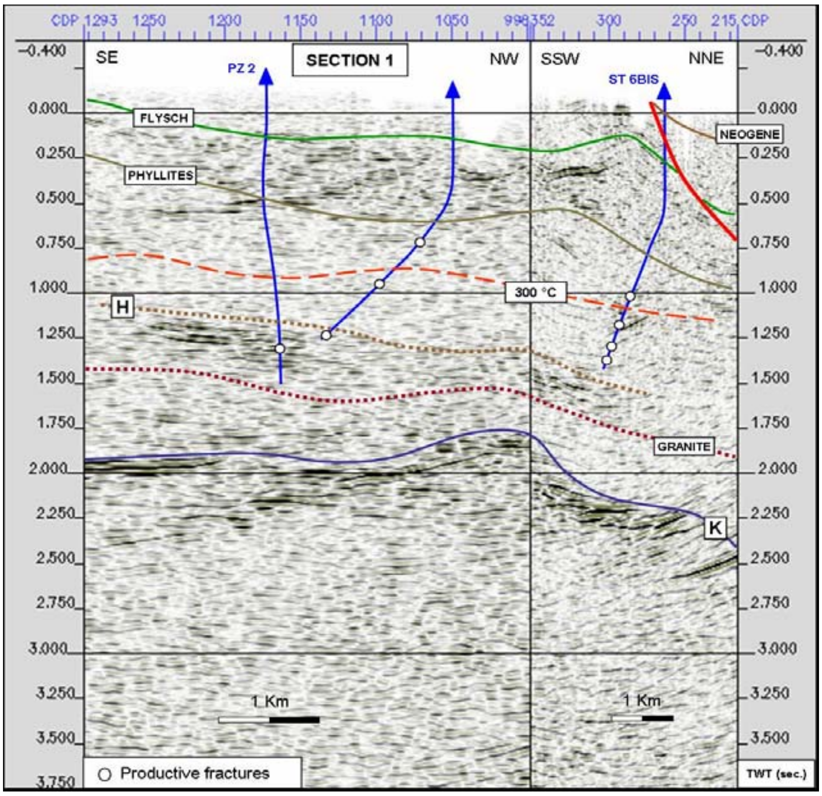

Figure 8: 2D seismic lines interpretation of the section 1 (see Figure 1) in the Sesta-Palazzaccio zone

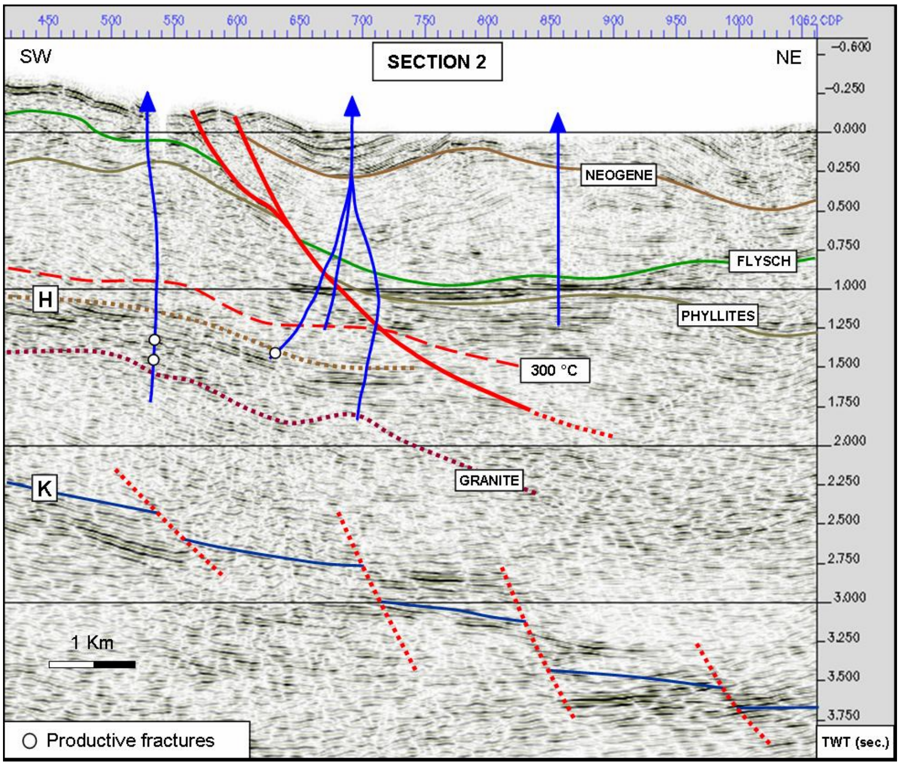

Figure 9: 2D seismic line interpretation of the section 2 (see Figure 1) in the Anqua-Radicondoli zone

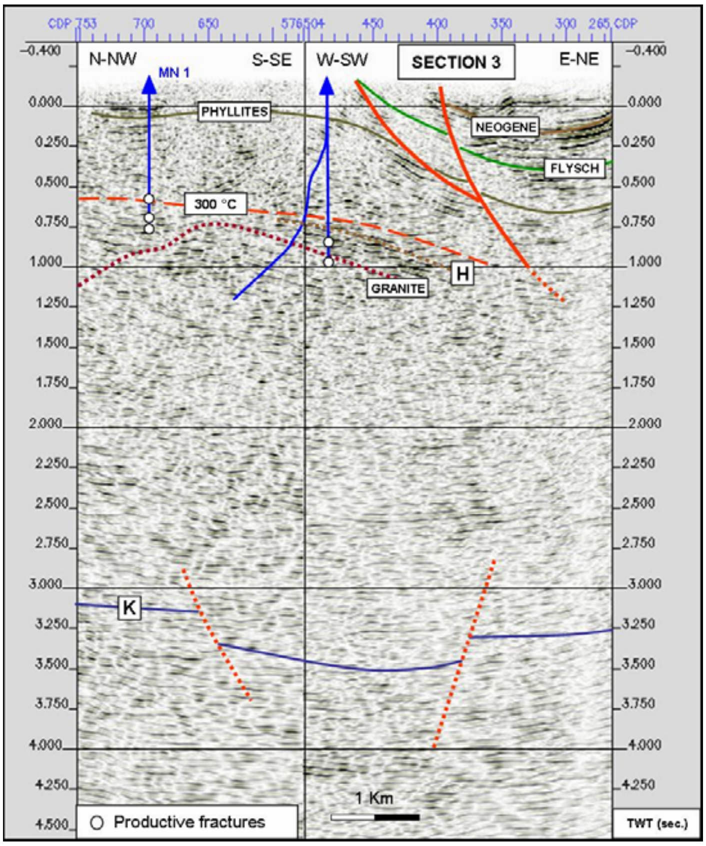

Figure 10: 2D seismic lines interpretation of the section 3 (see Figure 1) in the Montieri-Chiusdino zone

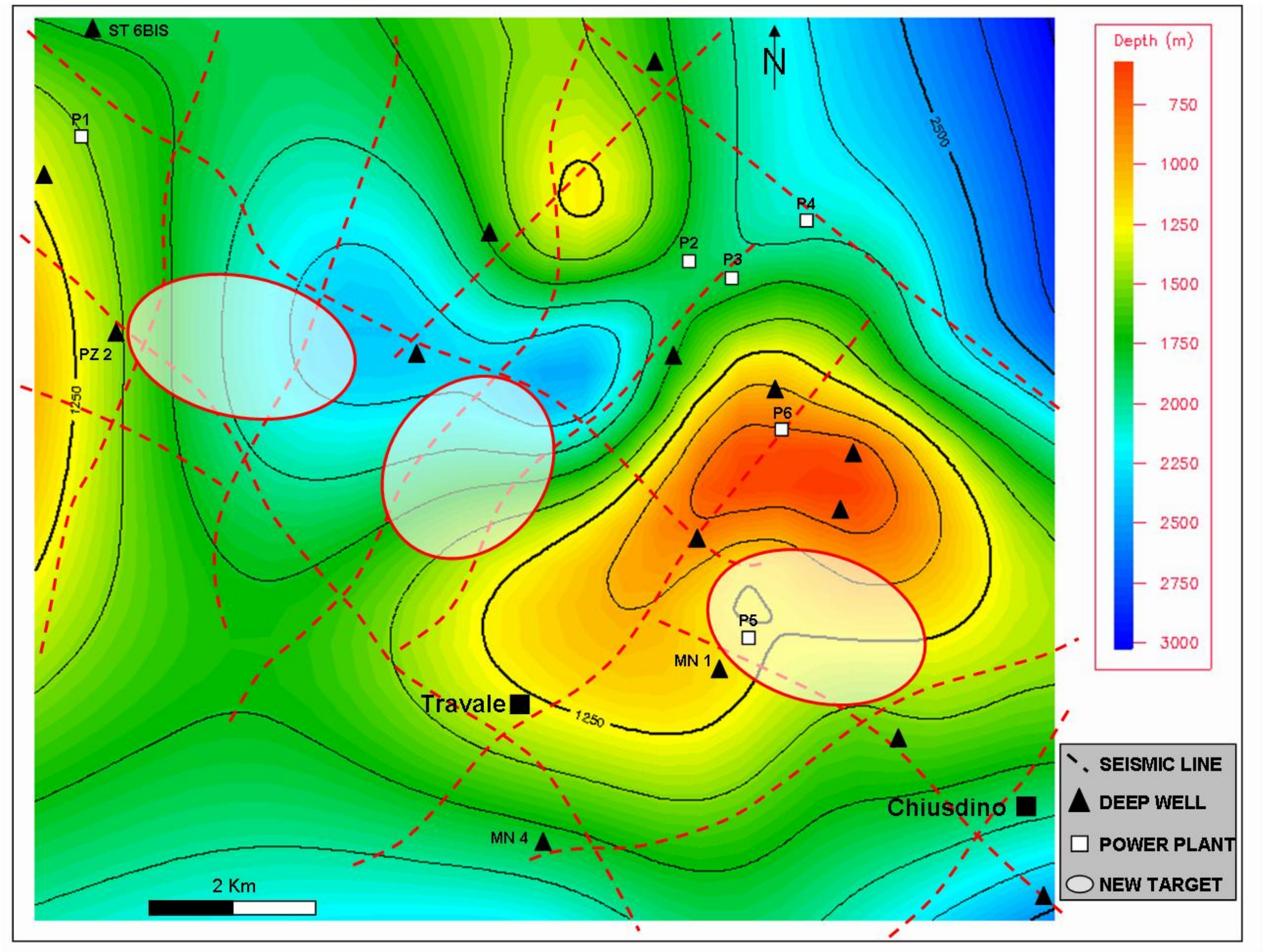

Figure 11: Map of the 270 °C isotherm depth in the Travale field. The zones of the new potential drilling targets are evidenced.