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3D Seismic Surveys and Deep Target Detection in the Larderello-Travale Geothermal Field (Italy)

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ABSTRACT

Deep exploration in the Larderello-Travale area highlighted a single deep geothermal system wider than 400 km^2 and with temperature of about 300°C at a depth of 3000 m. The deep reservoir is hosted in metamorphic/intrusive rocks and is characterized by a highly inhomogeneous permeability. This can increase the mining risk and, as a consequence, the drilling costs. A significant contribution in the detection of potential, productive targets for deep drillings can be provided by a detailed reconstruction of high amplitude seismic markers that, as confirmed by recent 3D seismic surveys, often correspond to fractured levels.

In the framework of a deep exploration project, new 3D surveys were performed in three areas of the Larderello-Travale geothermal system for a total full fold area wider than 100 km^2. Data processing was aimed at preserving the correct signal amplitude and at detailing the subsurface structures. An accurate joint interpretation of well and geophysical data allowed defining the 3D structure and the high amplitude anomalies of a seismic marker that shows a quite good statistical correlation with fractured and productive levels. This marker, known in literature as “H” horizon, is discontinuously present everywhere in the Larderello-Travale system, but can be originated by different or concomitant causes such as lithology changes and/or presence of fractured levels.

More than 10 directional wells have been drilled up to now to reach 3D seismic targets, but for the above said reason their productivity was different. The best results were obtained in the Travale area (3D Montieri-Chiusdino) where the H horizon corresponds to a highly fractured contact metamorphic aureole and where the correlation between well productivity and seismic marker suggests that more than 70% of steam production originates from depth intervals within this horizon.

1. INTRODUCTION

The exploration and exploitation of the Larderello-Travale geothermal system started at the beginning of the last century and initially interested a shallow reservoir, at depth less than 1000m. This is hosted in sedimentary formations (limestone and anhydrite), and has temperatures of about 250°C.

In the middle of 80s, the first deep exploration wells discovered, at depth higher than 3000 m b.s.l., a deeper superheated steam reservoir. This is characterized by temperatures of 300-350°C, (Barelli et al., 1995), pressure of up to 70 bars, and is hosted in metamorphic and intrusive rocks.

Subsequent deep wells confirmed that the deep Larderello and Travale fields belong to the same geothermal system, (Barelli et al. 2000, Bertani et al. 2005). This deep system is roughly delimited by the isotherm of 300°C at a depth of 3000 m, is wide more than 400 km^2 (Figure 1), but its real extension is not yet well defined. Furthermore the deep reservoir, differently from the shallow one, is characterized by a very inhomogeneous permeability distribution and this increases the mining risk and the drilling costs.

Previous studies demonstrated the reliability of seismic surveys in the Larderello-Travale area for locating deep fractured levels (Bertini et al., 2005), which are the productive drilling targets. In particular, a quite good correspondence between fracture systems and high amplitude seismic reflectors was highlighted in the metamorphic basement from a statistical analysis based on seismic 2D lines (Cameli et al., 2000). Furthermore, post-stack and pre-stack attribute analysis performed on 2D seismic data effectively pointed out a seismic anomalous zone with high reflection amplitudes and positive AVO gradients (Mazzotti et al., 2002) in correspondence of fractured levels.

This encouraged the use of 3D seismic surveys to identify potential targets prior to drilling thus reducing the mining risk. After a first test in a small area (Bruciano), three new surveys (see Figure 1) were scheduled in the framework of a new deep exploration program, (Cappetti et al., 2005), that envisaged the drilling of wells down to depths of 3500-4000 m, at the margins of mining licenses already under exploitation.

2. NEW 3D SEISMIC SURVEYS

The new 3D surveys were acquired in the period 2003-2004 with technical solutions aimed to guarantee a theoretic full fold ≥ 1600% for areas of about 34 km^2 at the maximum depth of the potential geothermal targets (4500 m b.s.l). Processing and interpretation were ended in 2005-2006 with the main purpose of providing specific targets for the deep wells to be drilled.

2.1 Acquisition

The acquisition parameters were defined as a compromise between costs and required data quality. Major importance was given to select energy source, bin size and theoretical maximum fold.

On the base of the previous 2D seismic data, explosive was preferred as the energy source. Shot holes 10-12 m deep were drilled and charged with about 3 kg of dynamite. Due to the irregular morphology and to the poor accessibility of all the surveyed areas, many shot holes were drilled by means of eliborne drill units.

A bin size of 25×40 m (50 m receiver group interval and 80 m shot interval) was chosen. The requested fold was achieved employing a source line spacing of 500 m and receiver line spacing of 480 m. The recording stations consisted in linear equispaced arrays of 12 geophones per group. Accessibility problems and environmental constrains caused a partial match between the planned and the real shot hole layout. This caused a heterogeneous coverage distribution but the requested minimum fold of 1600% was ensured in all the surveyed areas (Figure 2).

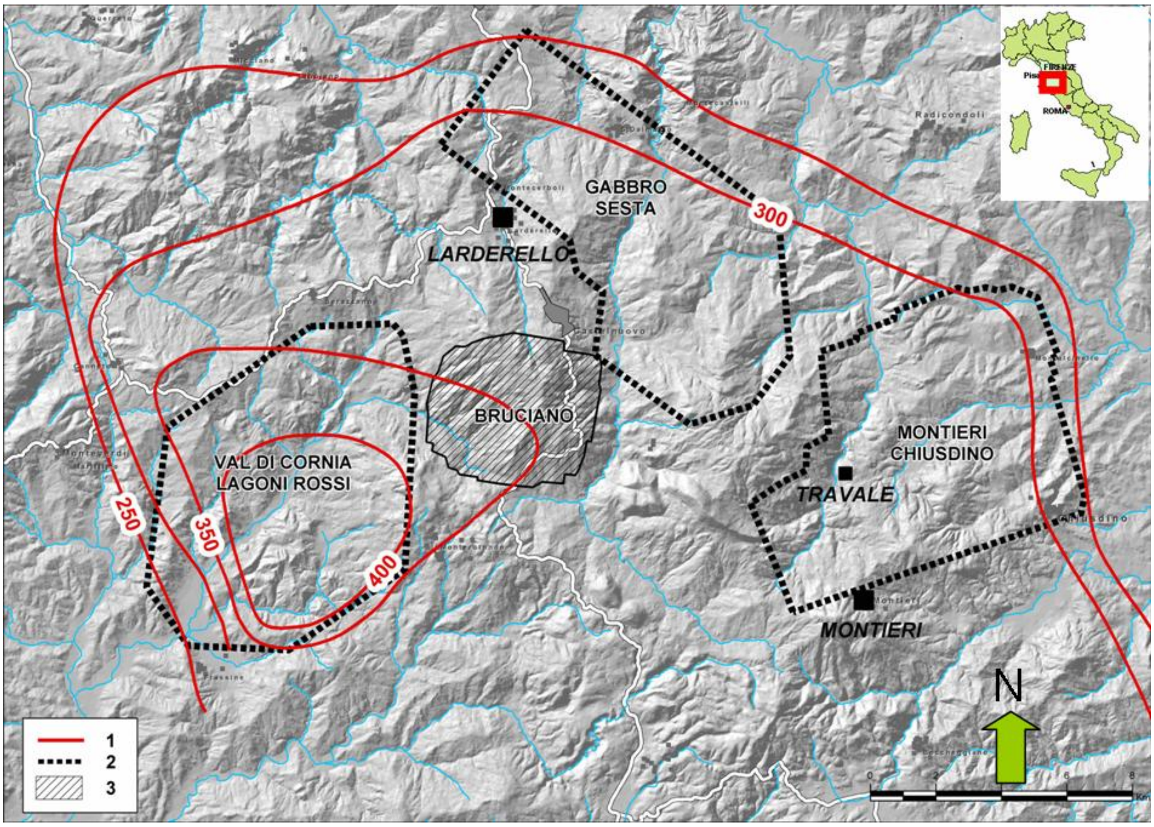

Figure 1: Larderello-Travale area. 1) Isotherms at 3000 m b.s.l.; 2) New 3D seismic surveys; 3) Previous 3D seismic survey.

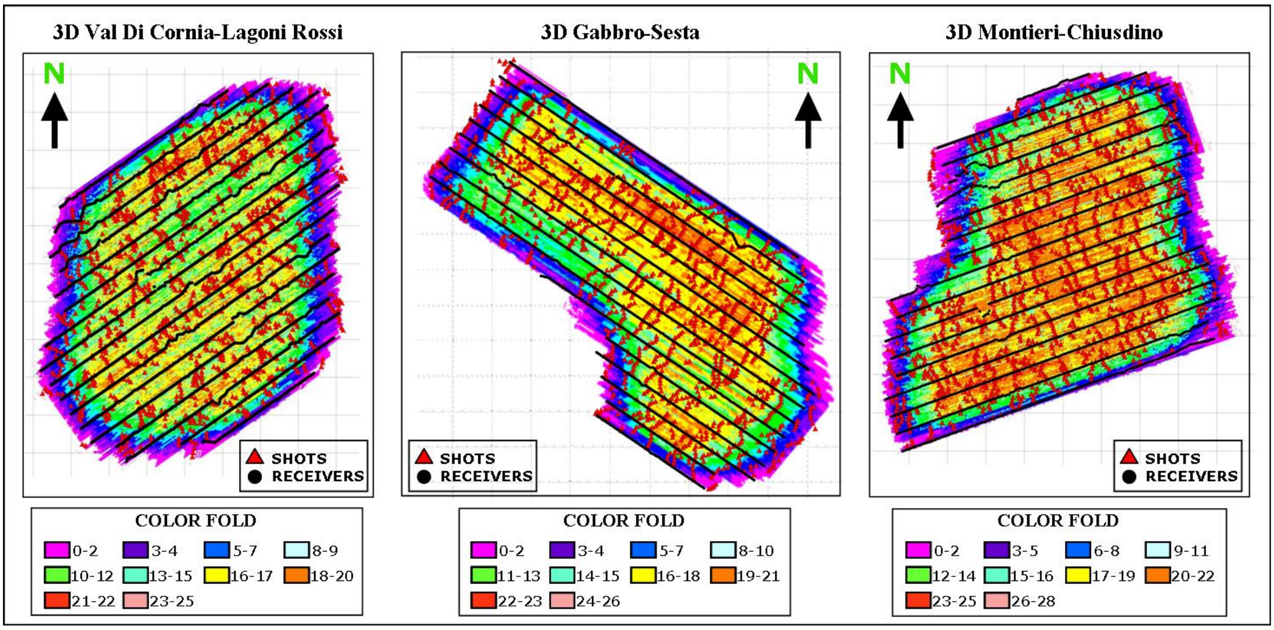

Figure 2: Actual acquisition layout and fold distribution in all the surveyed areas.

2.2 Processing

The same processing sequence was adopted for the three surveys in order to produce homogeneous data and possibly to attempt statistical seismic attribute analysis on the main seismic horizons. To this end, special care was devoted at recovering the true amplitudes of the seismic signals. The complete processing sequence is listed in Table 1.

Table 1: Processing sequence

PROCESSING SEQUENCE
Geometry assignment and bad traces removal
Statistical despiking
Band pass filter (4-8-70-80 Hz)
Refraction statics
Spherical divergence amplitude recovery
Surface consistent amplitude compensation
FX deconvolution in common shot domain
Predictive deconvolution
Velocity analysis
Selection and removal of noisy traces on the carbonate outcrop
Surface consistent residual statics
Refinement of the velocity field
Bin consistent residual statics
NMO and Stack
FXY Deconvolution
Post stack Kirchoff time migration

The whole Larderello-Travale area shows a strong variability in elevations (from 200 to 1000 m a.s.l.) and high lateral variations in the surface velocities. These characteristics requested a particular attention in the computation of statics and residual statics, and in the velocity analysis. The amplitude preserving approach suggested a limited use of multichannel filtering and of any operation which might cause artifacts. Offset dependent geometrical spreading and surface consistent amplitude correction contributed to restore the correct signal amplitude.

Local outcrops of carbonate formations required an additional processing step since they produced a strong energy absorption that affected the data down to the deep seismic markers. The removal of the noisy traces generated by both source and receiver placed on the carbonate outcrops was the adopted solution that improved the lateral continuity of the signals.

Due to the complexity and the high P-wave velocities peculiar to the geological bodies of the investigated areas, only a post stack Kirchoff time migration was applied. The adopted migration velocities were derived from the stacking velocity field after severe smoothing and reduction of the values. However, the final data obtained for the three surveys allowed the identification of the main deep seismic horizons (H and K) already evidenced by previous 2D seismic lines, (Cameli et al. 1994, Fiordelisi et al., 2005), in the whole Larderello - Travale area (Figure 3).

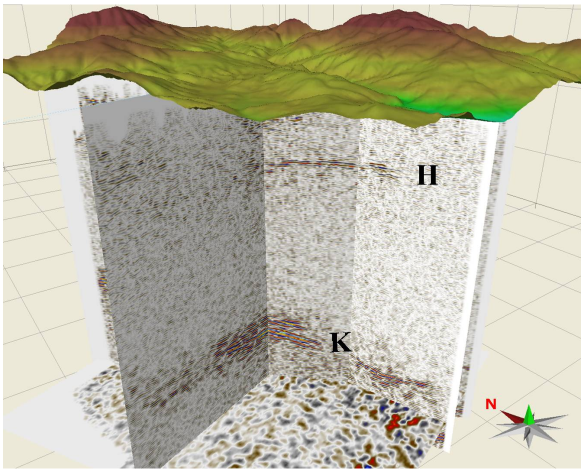

Figure 3: Three-dimensional view of the main seismic markers (H and K) evidenced in one of the 3D seismic volume.

2.3 Interpretation

The integrated interpretation of the 3D seismic with all the geological, geophysical, and well data allowed the update of the geological/structural model for the whole geothermal area and the identification of potential drilling targets. The interpretation was initially addressed to improve the structural reconstruction of the main geological horizons (Figure 4) and in particular the cap rocks formations (Neogene sediments and Liguridi Complex), the top of the Metamorphic basement (represented by phyllites, michaschists and gneiss), and the top of Pliocenic granites.

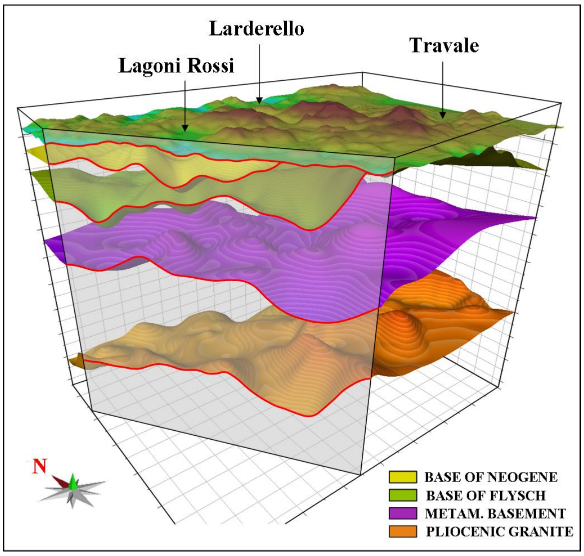

Figure 4: 3D reconstruction of the main geological horizons in the Larderello-Travale area.

The interpretation also allowed a detailed reconstruction of the strongest and deepest seismic markers H and K. The first one is located inside the metamorphic basement at about 0.6-1.4 s TWT. Although present over the entire Larderello-Travale area, it is discontinuous and its meaning can vary depending on different geological settings. On the contrary, the deepest K marker is quite continuous and shows the highest amplitude signals.

In the SE portion of the geothermal system, as testified by the wells, the Pliocene intrusions reach the shallower levels and the H marker is the expression of a contact metamorphic aureole. In the central area, where the intrusions are supposed to be deeper, the H marker corresponds to levels of skarn/hornfels underlying the presence of thin granites dikes. Finally in the western sector of the field, the H and K markers are almost in vertical continuity and it is difficult to distinguish one from the other. The K marker was never met by drillings and was entirely reconstructed by means of seismic interpretation. This horizon always runs below the top of the old granites (Pliocenic) at about 1.2 - 4s TWT. In a schematic geological model (Figure 5) this horizon was interpreted as a deeper, hotter and more recent (Quaternary) intrusion that embraces the entire Larderello-Travale geothermal field and could also control the temperature distribution with depth (Bertini et al., 2005, Bertini et al., 2006). In particular, the hypothetical 400°C isotherm is supposed to be coincident with the K horizon.

The second phase of the interpretation was aimed at the detection of potential drilling targets and was focused on the H marker. In fact, the high amplitude seismic signals characterizing this horizon can be correlated to fractured levels and hence to promising productive horizons.

For this reason a detailed picking of the H marker, both for the top and for the bottom, was performed to define its 3D structure (Figure 6) and to compute the RMS amplitude map for all the available 3D dataset (Figure 7).

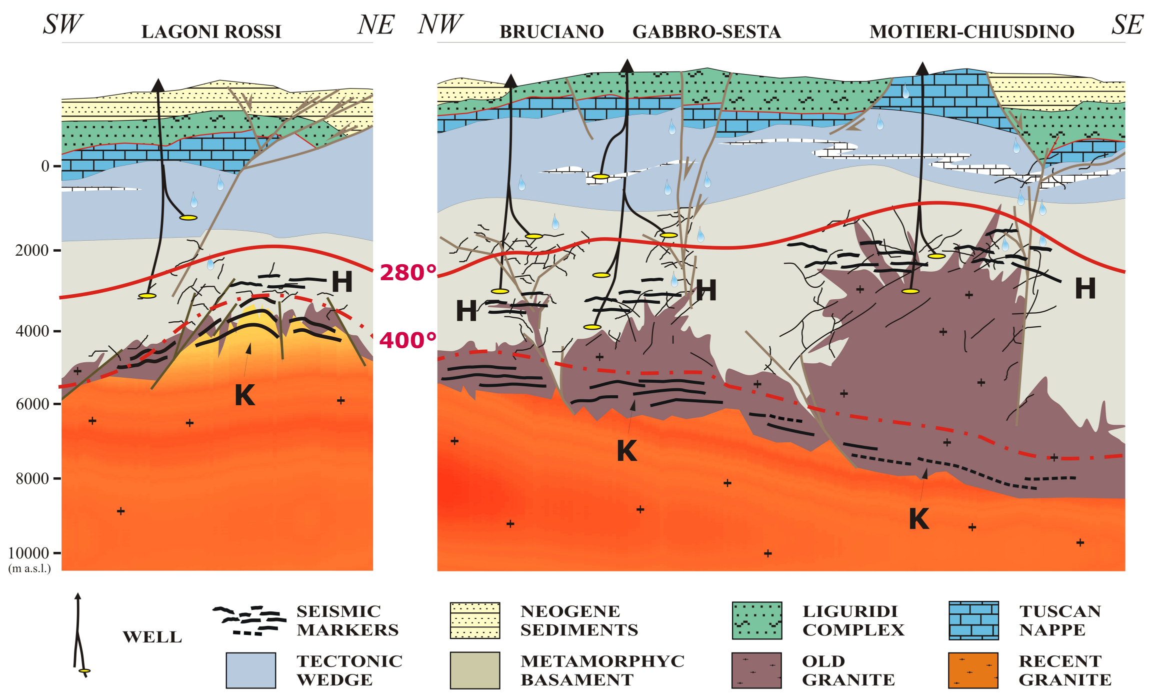

Figure 5: Schematic model of the whole geothermal system.

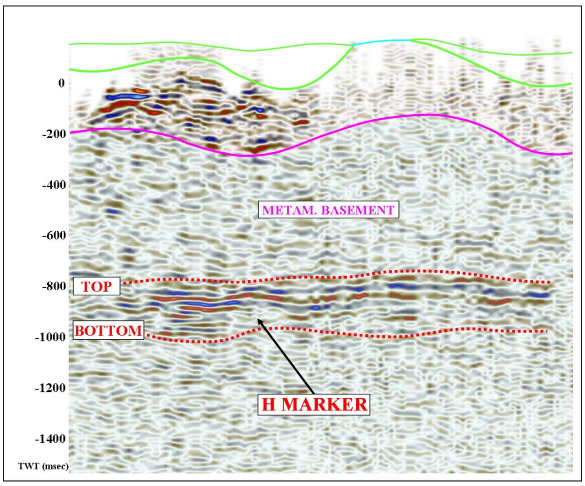

Figure 6: Random line extracted from 3D seismic volume showing the seismic signal corresponding to the H marker within the metamorphic basement.

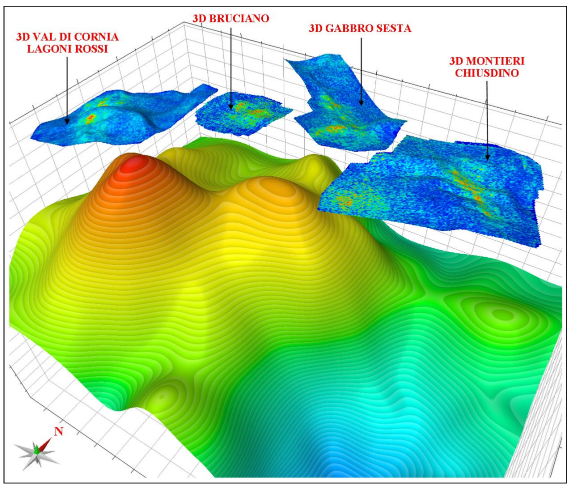

Figure 7: 3D view of the H marker top, with RMS amplitude maps computed for all the seismic surveys, and of the deeper K marker.

The most promising areas, which as above said are characterized by the highest amplitude values, were identified and indicated as potential targets for the deep drillings (Figure 8).

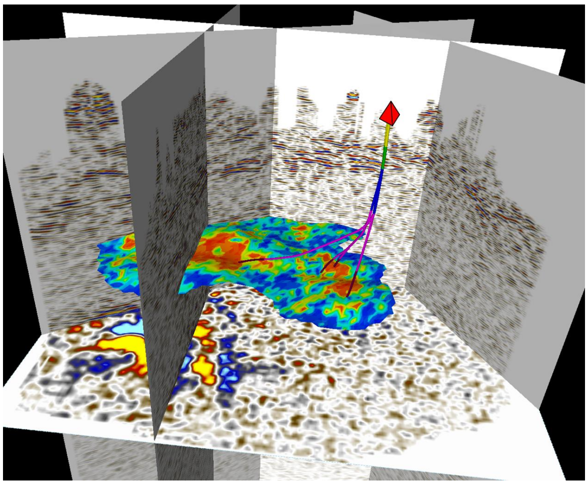

Figure 8: Example of high RMS amplitude values (red color) at the top of the H horizons and deep well profiles.

3. MAIN RESULTS

The experience acquired in more than 30 years of seismic data interpretation in the Larderello area proved that the H marker is often characterized by the coexistence of a high degree of fracturing and of local lithology variations. The meaning of this horizon, as a potential geothermal target, changes according to the geological-structural and thermobaric conditions of the field. In this framework, the emplacement of granites, their age and the geologic context of the host rock play a prominent role.

At the present, the H marker is the main seismic target identified in the Larderello-Travale geothermal system. On the basis of this deep target, ten wells have been drilled in all the 3D seismic areas and confirmed the strong relationship between the seismic reflections of the H horizon and the presence of fractured levels.

The RMS amplitude anomalies were helpful to detect, inside the H marker, more reliable potential targets prior to drilling. Indeed, well data have shown that although a correlation exists between seismic signal characteristics and the presence of fractured levels, there is no certain relationship with the degree of permeability of the fractured rocks. In other words, the productivity of a geothermal target cannot be evaluated on the base of the amplitude of the seismic signal.

From an industrial point of view, the best results were obtained in the Travale area (Montieri-Chiusdino 3D survey), where the H horizon corresponds to a wide contact metamorphic aureole. Well data evidenced the local increase of permeability and fracture occurrence characterizing this marker could be due to dissolution and hydrofracturing processes associated with over-pressured fluids released during the intrusion cooling phase.

In this area all the wells that crossed this seismic reflector were productive. Moreover, the correlation between fractures and seismic markers evidenced that more than 70% of fractured levels occurs within the H horizon (Figure 9).

A good correlation between H marker and fractured levels was verified also in the Gabbro-Sesta and Bruciano 3D surveyed areas (Figure 10). In this central area of the wide Larderello-Travale system the H marker is associated to thin levels of skarn and hornfels that are characterized by local increases of fractures and permeability. A quantitative study on the productivity of the H marker is ongoing for both areas.

In the western area (Val di Cornia – Lagoni Rossi), the lack of deep well data did not allow any direct correlation. In any case, the identification of the H marker as the potential target is affected by several uncertainties arising from the complex structural situation. In fact, the single well that probably reached the seismic horizon was stopped for a near blow-out occurred while drilling (Batini et al., 1983).

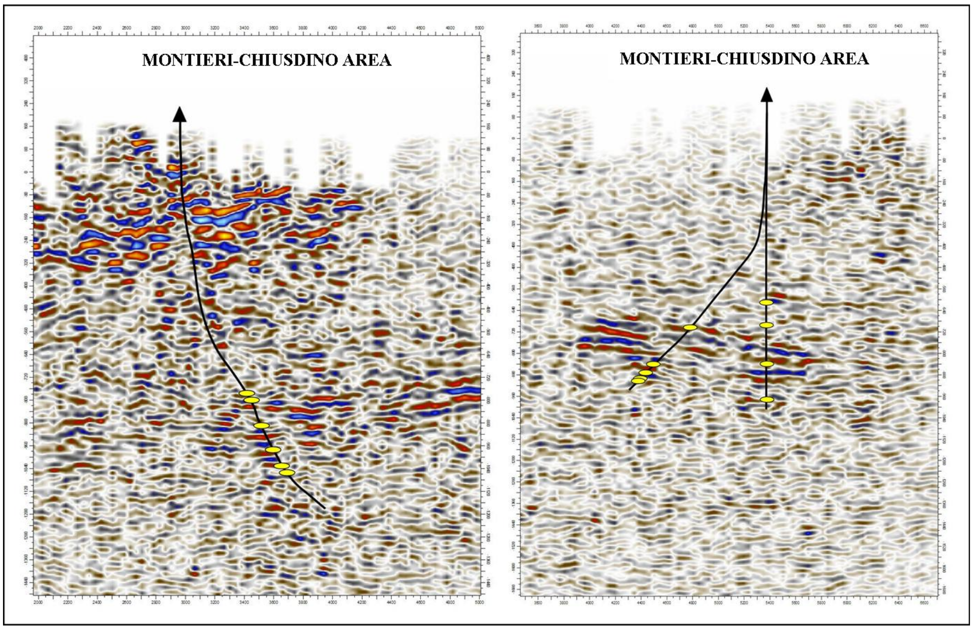

Figure 9: Example of some wells crossing the H marker in the Travale area. In yellow color the productive fractures.

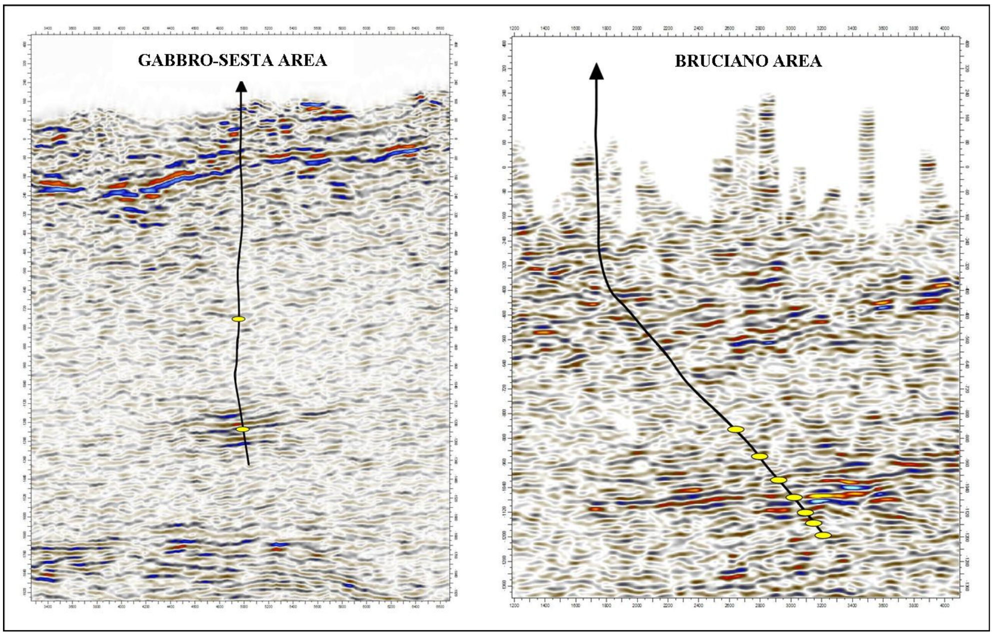

Figure 10: Example of some wells crossing the H marker in the central areas of the geothermal field. In yellow color the productive fractures.

In this area, the deeper K marker reaches its maximum apex (3000 m a.s.l.) and the relevant seismic reflections result to be often in vertical continuity with the above H marker (Figure 11). Thus, it is difficult to distinguish the two horizons and to characterize the seismic target. Furthermore, the thermobaric hostile conditions hypothesized in this area (> 400°C and 300 bars) do not seem to be compatible with the known geothermal reservoir so far exploited. In addition, the safety risks connected to a deep exploration are very prominent.

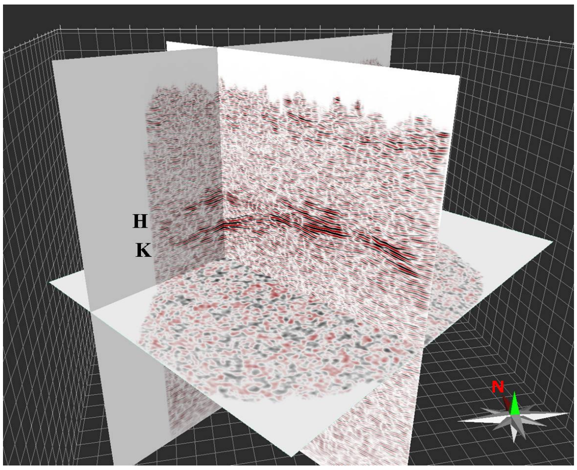

Figure 11: 3D view of the H and K markers in the Val di Cornia – Lagoni Rossi surveyed area.

Therefore, the good correlation between fractured systems, productive levels and seismic markers verified for the central and eastern areas could not be confirmed for the western one.

4. CONCLUSION

The availability of 3D seismic surveys and well data contributed to improve the understanding of the geological and structural context of the whole Larderello-Travale geothermal system.

The interpretation of the seismic volumes evidenced the H marker as the main seismic target identified in the area. It generally corresponds to the metamorphic aureole produced by the Pliocenic granitic intrusions. This marker is very often associated to the presence of fractured and productive levels, and its permeability seems to be related with the granite emplacement.

Amplitude analysis carried out on the H marker signals allowed the identification of drilling targets characterized by the presence of fractured levels. However, the relationship between seismic signal amplitudes and degree of permeability/productivity is more difficult to ascertain and it seems to vary for different areas. The best results have been obtained in the Travale area where more than 70% of steam production originates from depth intervals within this horizon.

REFERENCES

Barelli, A., Cappetti, G. and Stefani, G.: Results of deep drilling in the Larderello-Travale/Radicondoli geothermal area, *Proceedings* World Geothermal Congress, Vol. 2, pp. 1275-1278, Florence, Italy (1995)

Barelli, A., Bertini, G., Buonasorte, G., Cappetti, G., and Fiordelisi, A.: Recent deep exploration results at the margins of the Larderello-Travale geothermal system, *Proceedings* World Geothermal Congress, n. B6-2, (2000).

Batini, F., Bertini G., Bottari A., Burgassi P.D., Cappetti G., Gianelli G. and Puxeddu M.: S.Pompeo 2 deep well: a high-temperature and high-pressure geothermal system. 3rd Int. Sem., Geoth. Update, Eur. Comm., Munich, EUR 8853 EN, 341-353. (1983a).

Batini, F. and Nicolich, R.: The application of seismic reflection methods to geothermal exploration, *U.N. Seminar* on Utilization of geothermal energy for electric power production and space heating. Florence, Italy (1984).

Bertani, R., Bertini, G., Cappetti, G., Fiordelisi, A., and Marocco B.M.: An update of the Larderello-Travale/Radicondoli deep geothermal system, *Proceedings* World Geothermal Congress, (2005).

Bertini, G., Casini, M., Ciulli, B., Ciuffi S., and Fiordelisi, A.: Data revision and upgrading of the structural model of the Travale Geothermal Field, *Proceedings* World Geothermal Congress, (2005).

Bertini, G., Casini, M., Gianelli, G., and Pandeli, E.: Geological structure of a long-living geothermal system, Larderello, Italy, *Terra Nova*, 00, 1-7 (2006)

Cameli, G.M., Ceccarelli, A., Dini, I. and Mazzotti, A.: Contribution of seismic reflection method to the location of deep fractured levels in the geothermal fields of Southern Tuscany (Italy), *Proceedings* World Geothermal Congress, n. B6-3, (2000).

Cappetti, G., Fiordelisi, A., Casini, M., Ciuffi, S., Mazzotti, A.: A new deep exploration program and preliminary results of a 3D seismic survey in the Larderello-Travale geothermal field (Italy), *Proceedings* World Geothermal Congress, (2005).

Fiordelisi, A., Moffat, J., Ogliani, F., Casini, M., Ciuffi, S., Romi, A.: Revised processing and interpretation of reflection seismic data in the Travale geothermal area (Italy), *Proceedings* World Geothermal Congress, (2005).

Mazzotti, A., Zamboni, E., Stucchi, E., and Ciuffi, S.: Seismic characterization of Geothermal Reservoir: a case study in Western Tuscany, Italy, *64^th^ EAGE Conference and Exhibition,* Extended Abstract, Vol. I. n. C-37 (2002).