3D Seismic for the Deep Exploration of the Travale Geothermal Field (Italy): I-GET Project Results

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ABSTRACT

In 2003-2004 Enel carried out the acquisition of 3D seismic surveys in a few areas of the Larderello-Travale geothermal system.

In the framework of the European project "Integrated Geophysical Exploration Technologies for deep fractured geothermal system" (I-GET), advanced analyses have been applied to 3D seismic data of the Travale test site, where a deep superheated steam reservoir is hosted in metamorphic/intrusive formations at a depth greater than 3000m. Reservoir productivity is linked to fractured and permeable levels that are rather confined and not uniformly distributed and that often give rise to high amplitude seismic reflections. Thus, seismic data processing was aimed at the proper treatment of signal amplitudes and at the detection of the peculiar seismic signatures, as well as at the reconstruction of subsurface seismic images.

All the available surface and well data of the Travale site have been utilized for an integrated interpretation that was initially oriented to update the geological and structural model. Geophysical well logs were acquired in the framework of the IGET project, and together with all the other available logs, were very useful for calibrating surface seismic. A second interpretative step was the detection of deep seismic markers that can be interpreted as potential targets for explorative wells. To this end, pre-stack and post-stack signal amplitude analyses were focused on identifying areas characterized by anomalous amplitude values.

As testified by a significant number of wells, the most important deep seismic reflector in the study area is represented by the "H" horizon that, from a geological point of view, is the expression of a contact metamorphic aureole characterized by a higher fracture density. In order to assess the reliability of this seismic marker as a drilling and productive target, a detailed study has been carried out comparing the steam production from fractures occurring inside and outside the seismic horizon. As a result of this analysis the production supplied by fractures within the H marker was more than 70% of the total.

Introduction

The Travale geothermal area has been chosen as the Italian test site in the framework of the European project "Integrated Geophysical Exploration Technologies for deep fractured geothermal system" (I-GET). It is located in the E-SE part of the wide Larderello-Travale geothermal system, in Southern Tuscany (Figure 1). Geothermal activity in this region first started 100 years ago and exploited the shallow carbonate reservoir at a depth of less than 1000m. Since the 80's the exploration has been targeted to a deep superheated steam reservoir at 3000-4000m (Barelli et al., 1995, 2000). The deep reservoir is mainly hosted in the rocks

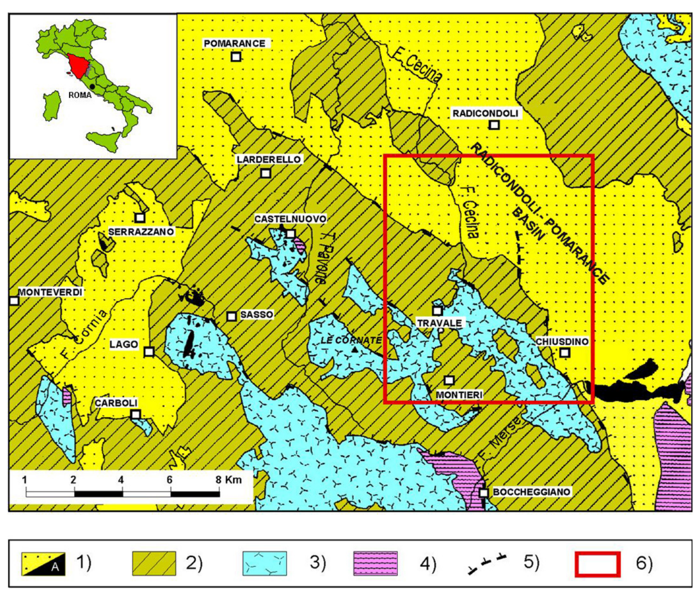

Figure 1. Location of the Travale test site and schematic geological map of the Larderello-Travale area. 1) Neogenic Sediments (A=Hydrothermal deposits); 2) Ligurian Flysch Unit; 3) Tuscan Nappe; 4) Metamorphic Basement; 5) Normal fault; 6) Area of the Travale test site.

of the metamorphic basement and shows a rather confined and inhomogeneous permeability. In this context, seismic reflection represents the most effective geophysical methodology to identify potential productive targets. In fact, the velocity and density decrease verified in correspondence to fractured levels (Cameli et al., 2000) can generate strong acoustic impedance (AI) contrasts and consequently seismic reflections detectable by surface seismic surveys. Studies performed on 2D lines evidenced anomalous zones with high reflection amplitude and positive amplitude versus offset (AVO) gradient (Mazzotti et al., 2002) that can be explained in terms of steam accumulation in fractured rocks.

The availability of a 3D seismic volume in the Travale test site, allowed a better reconstruction of the main geological structures and of the potential seismic target H horizon (Fiordelisi et al., 2005) located in the metamorphic basement. The availability of geophysical logs allowed the calibration of well and seismic data and the application of wavelet processing techniques that improved the interpretation reliability.

Amplitude analysis performed on pre- and post-stack data provided different results. Unfortunately pre-stack analysis gave few results while the post-stack investigation provided fundamental results for the target identification

Main Geological and Geothermal Setting

The Larderello-Travale geothermal field is a result of the tectonic evolution of this area which is part of the Northern Apennine chain (Bertini et al., 2006). The geological setting of the Travale test site involves, from top to bottom, Neogene sediments, Ligurian Flysch Units (Cretaceous-Eocene), Tuscan Nappe (Trias-Miocene sandstones and limestones), Tectonic Wedges (Permian-Trias anhydrites, quartzites and phyllites), Metamorphic Basement (Palaeozoic phyllites and micaschistes). In the lower part of this basement, contact metamorphic rocks (skarn and hornfels) can represent the aureole of the underlying granitic intrusions.

A geothermal model of the Travale field (Bertini et al., 2005) was reconstructed on the basis of the geological-geophysical and well data acquired in the past. Two different reservoirs have been identified:

- A shallow carbonate reservoir hosted at a depth of 500-2000m which is characterized by medium-high permeability with temperature ranging between 220 and 250°C.
- A deep superheated steam reservoir, in vapour-static equilibrium with the shallow one, hosted in the metamorphic basement and characterized by temperatures of between 300 and 350°C and pressure of about 7 MPa.

Recent wells revealed that the Larderello-Travale is a wide and unique geothermal field delimited by the 300°C isotherm that, at 3000m depth, includes an area wider than 400 km^2. The productive zones of the deep reservoir occur mainly within contact metamorphic aureole with temperature higher than 300°C. The lowest boundary of this reservoir still remains undiscovered.

3D Seismic Acquisition and Processing

In 2003 Enel acquired one of the 3D seismic surveys scheduled in the framework of a deep exploration program (Cappetti et al., 2005) in the Travale test site. Data were acquired with explosives as the energy source (1484 shot points) and a bin dimension of 25 x 40m. The actual acquisition layout (Figure 2) covered an area of about 60km^2, already investigated by deep drilling, and the required full fold of 1600% at the depth of the potential targets (about 4000m) was ensured for an area of about 33km^2.

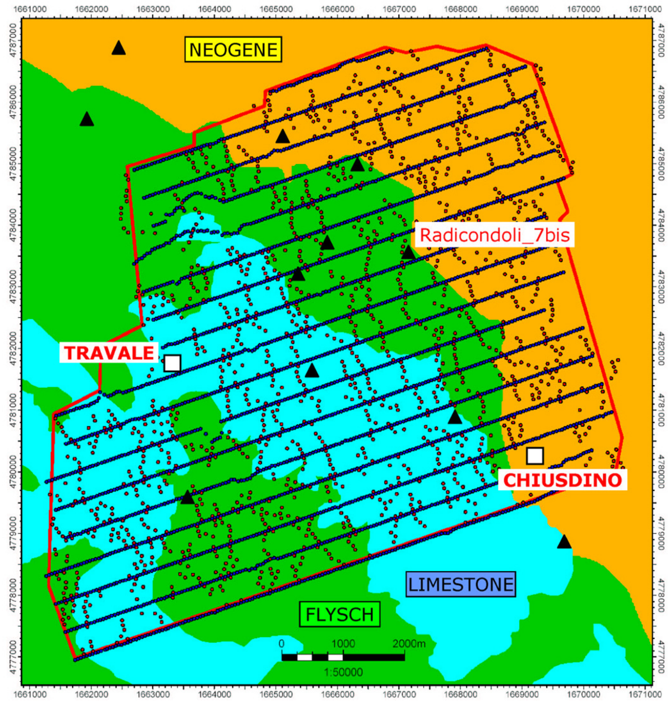

Figure 2. Actual acquisition layout, surface geology and main deep wells occurring in the area interested by the 3D seismic survey.

The processing was aimed at the reconstruction of the geological and structural setting and at recovering the true amplitudes of the reflected seismic signals. Due to the topographic complexity of the area and to the significant lateral velocity variations in the shallow layers, static corrections were a key step towards obtaining a good quality image of the subsurface. Densely spaced velocity analyses provided an accurate stacking velocity field which, after appropriate smoothing, was also used as input for the post-stack Kirchoff time migration. Surface consistent amplitude corrections were essential for true amplitude processing to compensate the non uniform efficiency of the shots and the different coupling conditions of sources and receivers. The application of pre-stack noise attenuation algorithms allowed an enhancement of the S/N ratio and the lateral continuity of the reflectors. The final processing enhanced the detection of two main deep reflectors already known in the Larderello-Travale area: the deep K horizon and the H marker that represents the most interesting seismic target (Figure 3).

Based on the final seismic data, advanced analyses were tried on pre-stack data to further understand the nature of the reflections. Unfortunately the acquisition template yielded a very narrow azimuthal coverage, strongly polarized along the in-line direction, and thus prevented any azimuthal analysis of the anisotropy. AVO studies provided further indications although limited to a few portions of the data due to the noise still contaminating most of the pre-stack data. In particular high values of the intercept attribute were showed in correspondence to the target reflections. This is

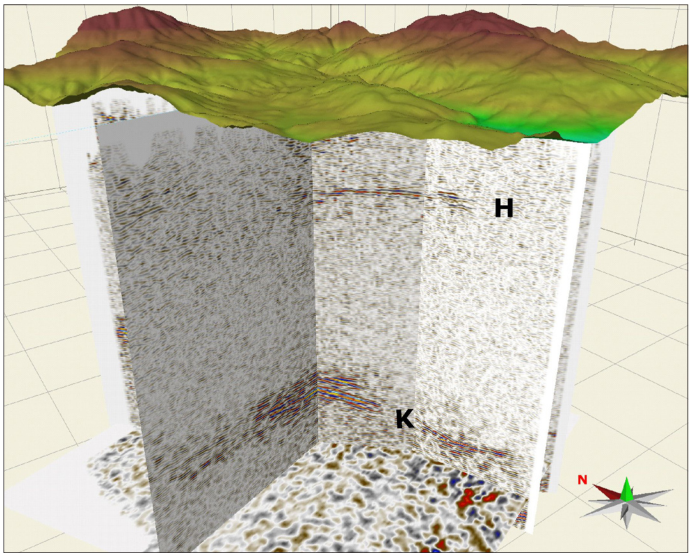

Figure 3. Seismic volume and main deep reflectors H and K.

consistent with the occurrence of high acoustic impedance contrasts at the top of the geothermal reservoir. In several cases, also the amplitude gradient of the main seismic target showed amplitude increasing with offset. However, it is yet unknown whether this is related to a fluid effect or to the presence of fractures or to other lithological factors associated with the existence of the reservoir.

Well Logging and Seismic Calibration

In the framework of the I-GET project a full set of geophysical logs, such as GR Spectralog, Induction, Density, Sonic, Vertical Seismic Profile (VSP), and Circumferential Borehole Image Log (CBIL), was acquired in the Radicondoli_7BIS deep well for the petrophysical characterization of the main geological units.

Furthermore sonic, density and VSP were acquired to calibrate the surface 3D seismic data and to identify the seismic response of fractured/permeable zones. In particular, an accurate time to depth conversion function and the reflectivity curve were obtained. Wavelet processing, performed on the 3D seismic stack trace nearby the well, enabled the focusing and shifting of the reflected signals to match the relevant reflection coefficients, improving the correlation between well log and seismic data. An up-shift of about 40ms was observed for the main reflectors and this, taking into account the velocity field, corresponds to a shift of about 100m.

Identification and characterization of potential fractures was also performed from log analysis. In fact, sharp decrease of density and velocity values and significant variations of acoustic impedance are usually due to fractures. These are also characterized by strong attenuations of the Instantaneous Amplitude (IA) as verified by waveform analysis of the sonic log (Figure 4).

CBIL was finally acquired to investigate intervals showing the most evident attenuation of seismic energy. CBIL analysis allowed the fracture characterization in terms of classification and geometrical reconstruction (see Figure 4). Fracture attitude resulted as consistent with a fracturing model characterized by high angle fractures (70-85°) mainly oriented in NW-SE direction and dipping toward NE.

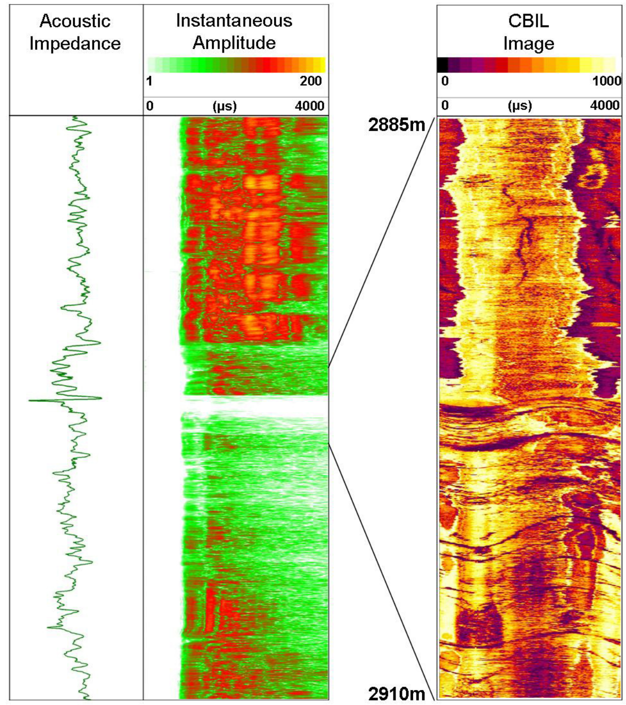

Figure 4. Fractured level evidenced by CBIL and characterized by strong absorption of acoustic energy and AI decrease.

Interpretation

An integrated interpretation of all the available data was performed to update the geological and structural model of the area and to identify deep seismic markers that could be potential drilling targets. As regards the previous 2D seismic outcomes, 3D survey provided a better definition of the reflector geometries and the main geological horizons below Neogenic sediments, such as

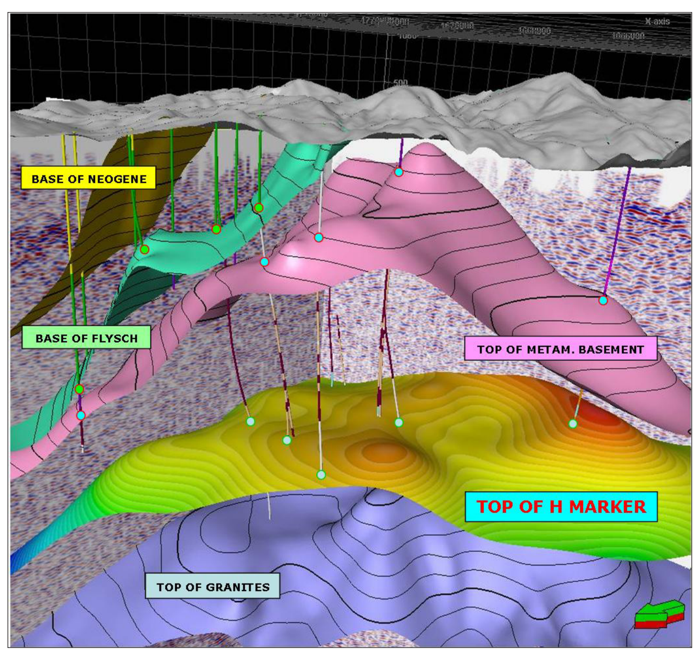

Figure 5. Main geological surfaces and seismic horizon (H and K) reconstructed from 3D seismic interpretation.

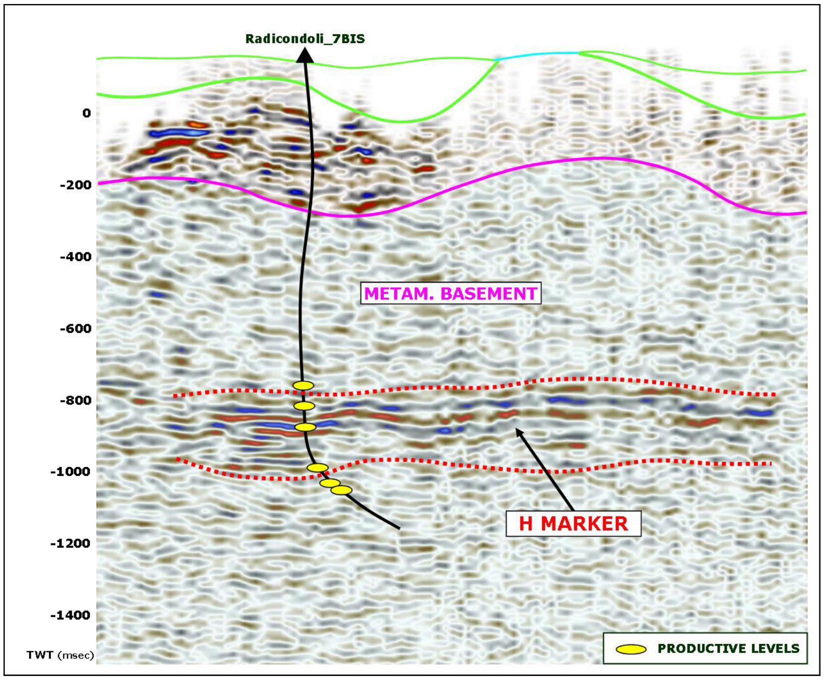

Figure 6. H marker and fractured levels identified in the Radicondoli_7BIS deep well.

expression of a contact metamorphic aureole (skarn and hornfels). For this reason the H marker interpretation also allowed a better definition of the structural trend of Pliocenic intrusions that caused the aureole. The deeper and stronger K marker, well known in literature (Cameli et al., 1993), was never reached by drillings and hence it was entirely reconstructed by seismic data only.

The interpretation aimed at the target detection was focussed on strong seismic markers inside the metamorphic basement because, for its general homogeneity, high amplitude seismic signals can be correlated to fractured levels and hence to promising productive horizons (Figure 6).

In the study area, H marker is the most important reflector that can be linked to fractured levels, but, for its geological meaning, the high amplitudes and strong reflections that characterize it can be generated by the combined effect of lithological variations (contact metamorphic aureole) and of higher occurrence of fractures. For this reason an amplitude analysis of the H horizon was performed (Figure 7).

H marker was matched up to well testing data to estimate the contribution of each single fracture to the total production. Geophysical logs were also compared both with the fractured levels and 3D seismic images in order to improve the integrated interpretation and to provide a better target characterization (Figure 8).

A significant correlation between seismic reflections and productive levels was verified analyzing the average production inside and outside the H marker of 24 deep wells in the 3D surveyed area (Figure 9). Among these, 13 wells met the H horizon and are productive, while 8 of the 11 wells located outside this horizon resulted unproductive.

Furthermore, the results of this analysis indicated that the production supplied by fractures occurring within the H marker is about 77% of the total, while, in terms of t/h/km, the productivity coming from this marker is more than 80% of the total.

the bottom of Flysch, the top of the metamorphic Basement and the top of Pliocenic granites (Figure 5).

Among the seismic reflectors, special attention was given to the analysis of the H marker that constitutes the potential drilling target, being at attainable depths in the metamorphic basement. Well data clearly showed that, in the specific area of Travale, this horizon is located above the top of Pliocenic granites and is the

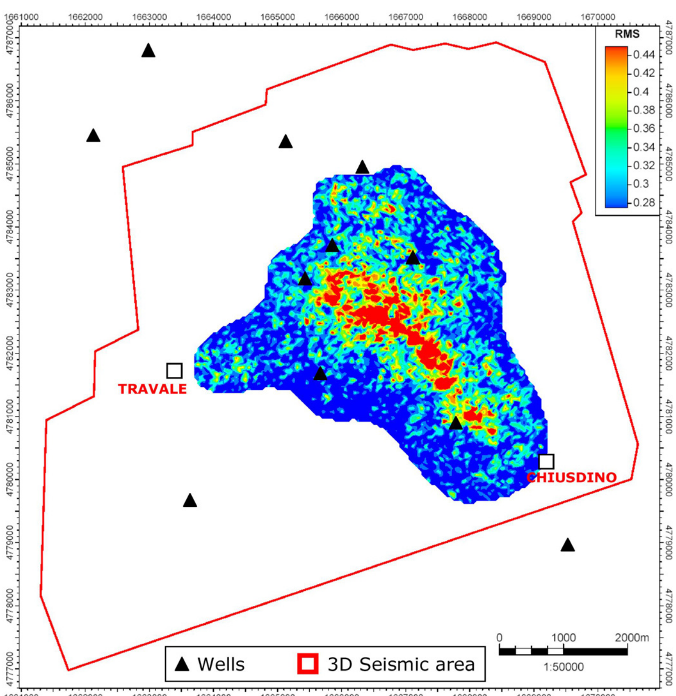

Figure 7. RMS amplitude Map of the H horizon.

Conclusion

The interpretation of the 3D seismic survey acquired in the Travale test site allowed a detailed reconstruction of the geological/structural model of the area and the identification/characterization of potential drilling targets. These have been identified through the detection of high amplitude anomalies in the H seismic marker that is hosted in the metamorphic basement.

The integrated interpretation with all the well data highlighted that the H marker corresponds to a contact metamorphic aureole. This can be strictly connected to the emplacement of granitic bodies and is characterized by a locally high fracture density.

In the Travale test site, the reasonably good correspondence between productive levels and seismic targets showed the reliability of seismic method for the detection of fractured levels, defining the H marker as a potential drilling target.

Currently in the 3D seismic area 24 deep wells have been drilled:

- 13 reached the H horizon and are all productive

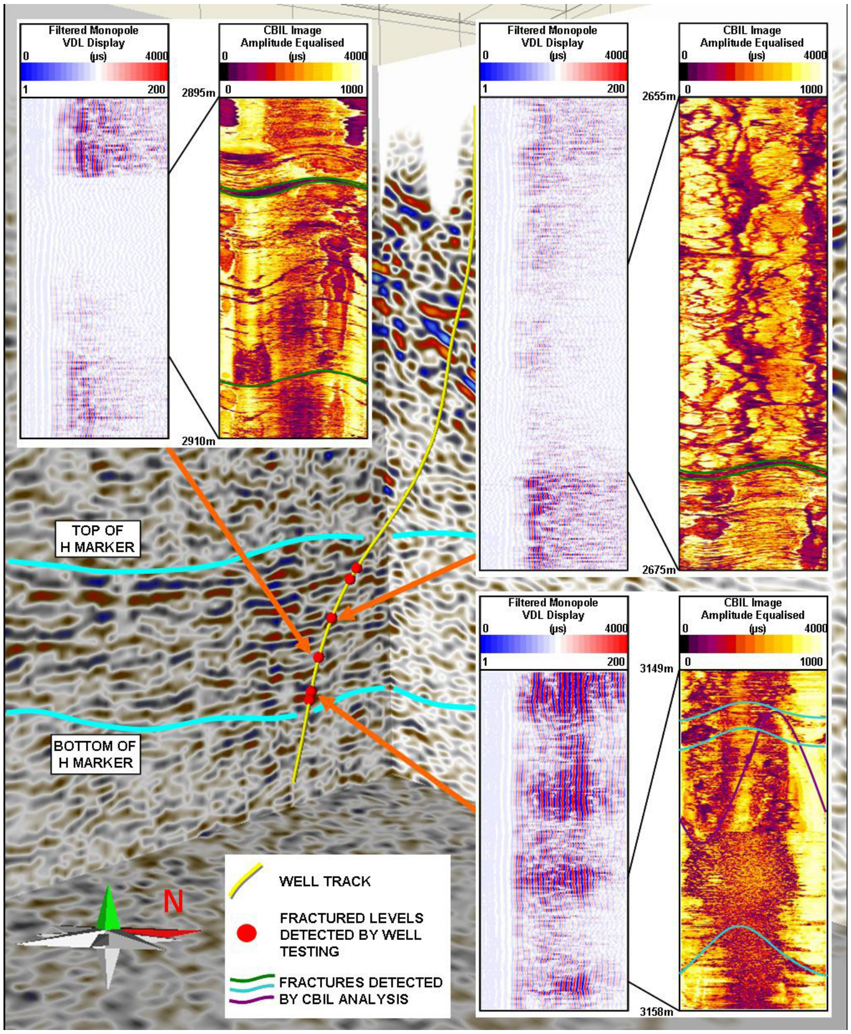

Figure 8. Correlation between fractured levels form well testing, 3D seismic and well log data.

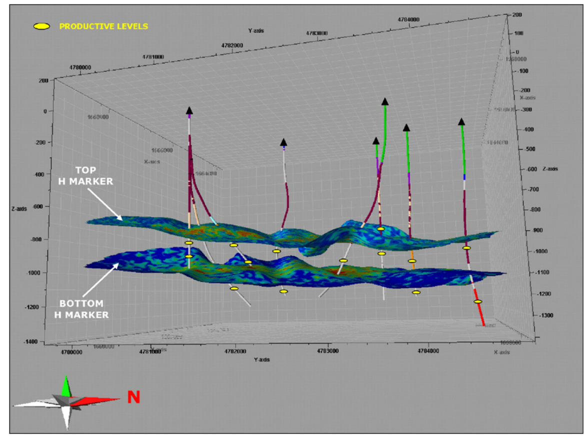

Figure 9. Correlation between productive levels and the seismic H horizon.

- 11 did not reach the H horizon and only 3 of these are productive.

Production from the H horizon represents more than 70% in terms of t/h and more than 80% of the total in terms of t/h/km.

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