

## Revised Processing and Interpretation of Reflection Seismic Data in the Travale Geothermal Area (Italy)

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### ABSTRACT

Despite difficult conditions, such as rough topography and complex geological structures, reflection seismology is now recognized as a successful method in the detailed exploration of the deep geothermal steam reservoirs of Tuscany (central Italy).

In the presented work, a unified approach is adopted for both data re-processing and interpretation. The aim of seismic re-processing is to provide a common signature for lines recorded at different times and with different procedures.

During re-processing, emphasis is put on detailed velocity analysis and trace amplitude consistency. Consequently, it is now possible to sharpen the seismic image at greater depths and to identify interesting seismic lineaments that can be related to deep exploration targets.

The interpretation of seismic data is supported by: surface geology, well logs, core descriptions and temperature profiles. This data is jointly visualized at workstations and attributes of interest (typically seismic amplitudes and well logs) are extracted and highlighted.

This unified approach reduces uncertainties in interpretation and gives confidence in describing the structure of the area. Here it consists of extensional faults affecting a deep, prominent reflector of regional importance (K Horizon). The high-amplitude reflectivity of this reflector suggests gas/steam accumulations. Similarly, high amplitudes also characterize a shallower and discontinuous reflector (H Horizon).

As a result, reflection seismic enhances the comprehension in the area of study and provides the structural framework contributing to build-up the overall reservoir model.

### 1. INTRODUCTION

The deep exploration of the Larderello and Travale geothermal fields (Tuscany, Central Italy) started 25 years ago with drilling exceeding 3000 m depths, in high temperature and pressure conditions across metamorphic and intrusive rocks, e.g. Barelli et al. (1995, 2000).

This exploration task was quite challenging with respect to the previous exploration in the shallower carbonate rocks. While the shallow reservoir consists of distinctive fracture systems, assuring high permeability and steam production, the deep reservoir displays an uneven distribution of fractures. This is testified by highly variable fluid flows,

ranging from a few to a maximum of 300 t/h, in nearby wells.

At a greater scale of observation, the deep reservoir of the Larderello and Travale fields became a unique geothermal system, covering 400 km<sup>2</sup>, and having temperatures over 300°C at 3000 m (Figure 1).

Surface seismology played a key role in the identification of deep geothermal targets decreasing the mining risk and optimizing the high drilling costs. As consequence, deep drilling has been highly rewarding, particularly in the Travale area, that shows a high potential for further development.

In this report, we shall describe how 2D seismic lines, acquired with different techniques over more than twenty years, have been recently reprocessed, updated and reinterpreted to improve the knowledge of this part of the deep field and guide the ongoing development.

### 2. NEW 2D SEISMIC PROCESSING

Approximately 230 km of 2D seismic lines were acquired in the Travale area in the recent deep exploration phase (Figure 2).

These lines were shot in four data vintages (1976-78, 1986-87, 1993 and 2000) to address specific problems in the area. Consequently, the quality of the seismic images largely depends on the state-of-the-art of seismic techniques during those years.

The oldest surveys adopted dynamite explosive sources and 48-channel receiver arrays. Due to the rough topography of the area, the nominal fold is no greater than six. In summary, the dynamite energy source allowed an unprecedented depth of penetration, but the poor coverage was not favorable to lateral resolution.

Contrary to this, lines acquired since the late eighties were recorded with vibrator-truck sources and longer arrays of 96-192 channels. The main benefit was a superior nominal fold (24 to 32) leading to a better lateral consistency.

The greater amount of data, however, poses a problem of data consistency with regards to both data processing accuracy and seismic signal signature.

#### 2.1 Processing Procedures

In the recent re-processing, the four seismic vintages have been treated as a single overall dataset, with a uniform approach. In the adopted sequence, a special emphasis has been given to the following steps:

- Crooked line geometry reconstruction, in place of previous coordinate linearization.
- High-resolution static corrections, based on refracted and reflected shallow arrivals, computed every two CDP gathers
- Surface consistent deconvolution, to properly balance seismic amplitudes
- High-resolution velocity analysis computed every two CDP gathers
- Two types of stacking data reduction. A) In the true amplitude stack, emphasis is given to preserving the original reflectivity, i.e. the relative contrast of stratigraphic acoustic impedance. This reflectivity is thus closely linked to rock physic properties such as mineralogy and fluid content. B) In the structural stack, emphasis is given to lateral reflectivity. The resulting sections highlight geological variations and facilitate the tracking of horizons and faults.
- Migration is performed by Kirchhoff-type diffraction stacks on both true-amplitude and structural stacks. It benefits greatly from the high-resolution velocity analysis.

## 2.2 Data Improvement

The first beneficial consequence of the surface seismic re-processing was the improved interpretation of the seismic images. Notably, the vertical length of the seismic wavelet was greatly reduced. Due to improved static corrections, the events were consistently located at the appropriate two-way time and mis-ties at line intersections virtually disappeared. Structural artifacts created by out-of-plane reflections were also greatly reduced.

But, even more significantly, the new images have given a greater confidence in the geometrical delineation of the events of interest. Figure 3 shows how high-amplitude bodies can be better isolated from the background reflectivity. A structural application is illustrated in Figure 4, where a major normal fault outstands clearly in the re-processed section on the right hand side.

The amplitude and structural characterization has been improved in particular for the two main and deep markers of the area, the already known K horizon e.g. Batini and Nicolich, (1984), Cameli et al, (1993) and a second one, called H in this paper. Since both these deep seismic signature have a meaningful role in the geothermal features, the data improvements fit with the original purpose of reducing the uncertainty in exploring the deep geothermal reservoirs in the study area.

## 3. DATA ANALYSIS

Once the consistency of the surface seismic dataset had been achieved, the following step was to correlate the time domain seismic data with the depth domain well data, such as core descriptions, markers, log curves, etc.

### 3.1 Software and Workflow

This evaluation was accomplished by adopting commercial interpretation software, commonly utilized in the hydrocarbon exploration industry.

The collected data resides in a dynamic database, which can be updated as new data is acquired. The well information (deviation profiles, markers, log curves) is associated with depth-time conversion tables that allow an immediate visualization of well features onto a seismic line at a consistent vertical scale. This joint visualization triggers the lateral tracking of stratigraphic horizons and fault discontinuities.

As the tracking operation proceeds, the horizon is mapped aerially to display its 3D geometry. Several interpretation hypotheses can be tested and crosschecked during the same interpretation session, to further reinforce confidence with the results. The goal of the overall workflow is to provide reliable information to the subsequent stage of reservoir modeling (Figure 5).

### 3.2 Geophysical Log Integration

A considerable amount of well data has been utilized to support the interpretation of the re-processed seismic lines. In approximately 93 wells, key markers at lithological boundaries, faults, and fracture zones can be identified and correlated from well to well. These markers can then be concurrently displayed on the seismic cross sections and used to control the tracking of both faults and litho-stratigraphic boundaries.

The time-depth relationship has been obtained by Vertical Seismic Profiles and check-shots recorded in 14 wells. This information allows one to compute typical formation velocities and to extend the time-depth control over all the study area.

Classical well logs, such as Gamma Ray, Sonic, Density and Neutron log, are available in about 15 wells. These logs are important in identifying stratigraphic markers and, additionally, in focusing which (and how) petrophysical properties are responsible for the observed seismic response. The Sonic and Density log curves have been used to generate synthetic seismic traces that are comparable to the real seismic traces. In the example of Figure 6, the thickness/amplitude variations of the Sonic log testify an anhydritic interval and account for the high-amplitude reflectivity on seismic section.

### 3.3 Well Seismic Profile Integration

The good example shown in Figure 6 is not generally valid. Some important variations in GR radioactivity have no velocity variation in acoustic velocity and hence no seismic expression. In addition, well logs are seldom recorded in the deep and hot sections of the wells. In these cases, we rely on Vertical Seismic Profiling (VSP), a technique able to predict the petrophysical response of layers located below the maximum depth reached by the logging tool (Figure 7).

In the study area, VSP data describe homogeneous velocities in the deep metamorphic reservoir, e.g. Oglioni et al. 2004, with two notable exceptions at H and K reflections. In these levels, we observed a local decrease of acoustic impedance (i.e. low velocity and low density) restricted to relatively thin intervals. Local concentrations of gaseous fluids (steam for instance) are sufficient to generate a high acoustic contrast against the surrounding massive rocks and, consequently, high amplitude reflections. The conclusions are valid for both K and H reflection on a punctual basis.

#### 4. STRUCTURAL INTERPRETATION

Since the first examination of the seismic lines, the shallow geology appeared quite distinct (or even disharmonic) from the geology of deepest parts.

For the purpose of deep geothermal exploration, only the major events of the shallow geology have been considered. In tectono-stratigraphic terms, these shallow units mainly consist of:

- clastic fills of Neogene extensional basins formed following the main build-up the Apenninic chain
- various Mesozoic-to-Tertiary units, overthrust and piled-up by polyphasic tectonics.

The interpretation of these units essentially addresses the comprehension of the underlying sections.

In practical terms, the high-reflectivity signal of Triassic anhydrites generates the seismic event separating the better-understood, shallow, sedimentary section from the deeper metamorphics.

Underneath the anhydritic reflection, the Palaeozoic rocks underwent regional metamorphism which increases with depth, i.e. ranging from phyllites to micaschists and gneiss. Thermo-metamorphic rocks and recent granites have also been encountered by deep drilling. On seismic sections, this natural complexity is masked by homogeneous petrophysical behaviour, with the outstanding exceptions of the deep K reflection, e.g. Batini and Nicolich 1984, Cameli et al. 1993, and the shallower H reflection.

For these reasons, the K and H reflections are the main events that drive the interpretation of the deepest part of the Travale geothermal reservoir.

##### 4.1 The K horizon

The K horizon is the high-amplitude, laterally persistent and deepest acoustic event in the study area. Vertically it is made of short resonant reflections of variable thickness (Figures 8 and 9).

The geological context of the K horizon is still poorly known due to the lack of direct observations. However, regardless of its physical meaning, the K reflection can be treated as a lithological horizon.

The overall interpretation of the reflection surface highlights a single geological body, whose maximum elevation is located in the Western part of the area at 2 s two-way-time, approximately 5000 m depth. The horizon gradually deepens to the South and more abruptly towards East where it is found at 5 s twt, i.e. more than 12000 m (Figure 10).

On the reprocessed seismic sections, the K horizon is often clearly broken by discontinuities (see Figure 8), which interrupt and displace this signal. The broken nature of the K reflection allowed us to trace these discontinuities as high-angle faults.

Usually, these deep faults underlie the zones of recent tectonics that generated shallow Neogene basins, but the upward extension of these faults requires a great deal of approximation. A direct connection with the shallow faults is not proven with certainty and we describe the structure only in the context of deep-seated fault planes that can be traced with high confidence.

In spite of these difficulties, it is possible to infer a disharmonic development of the shallow and deep structures that may be related to the intrusive activity of the granite emplacement.

Four main discontinuities have been identified at the K level and interpreted as extensional faults (see Figure 10). Three of them strike parallel to the NW-SE Apenninic axis. The dip angle is 60-70 degrees and they plunge to the NE. The overall attitude is step-wise, progressively downthrown towards NE. The vertical displacements are usually small with the exception of the fault located farthest to NE.

The fourth fault stretches with a N-S orientation as a steeply dipping or vertical plane and horizontally displaces the earlier Apenninic faults with a dextral movement, revealing a younger transcurrent behaviour.

Most of the observations converge in their description of the stress-strain conditions at the K level, where high temperatures are expected. The faulted pattern describes an elastic mechanic behaviour, presumably of quite recent origin, that leads to a new conceptual model, e.g. Bertini et al., this volume.

##### 4.2 The H horizon

The H horizon is a reflective band located above the K horizon at a shallower depth. Its appearance consists of laterally juxtaposed bright-spot reflections. In many respects, it resembles the K reflection, but displays lower amplitudes and lacks lateral continuity. Although it is discontinuous, the H reflector does not appear to be cut and displaced by major faults.

In the Northern parts of the area, the H reflection is conformable to the K reflection, with a vertical separation of 700 ms twt (approximately 1750 m). Towards the SE, the two signals strongly diverge, as the K horizon descends and the H rises. The thick separation distance (some 5000 m) suggests that the two events are not genetically correlated in this part of the area (see Figure 9).

Contrary to the K, the H horizon is thus located at depths can be attained by drilling. Four wells have penetrated the H reflector, encountering highly permeable fracture systems with important production of steam. This outcome confirms the VSP predictions performed before deep drilling.

The host rock of the fracture systems consists of thermo-metamorphic rocks of various origins. At greater depth, all of the four wells have encountered granitic rocks crystallized in late-Pliocene – early Pleistocene time (dating about 2.5 Myr). These granites testify a relatively recent intrusion, responsible of the thermo-metamorphic halo where the H event resides.

As supported by the drilling data, therefore, the H event is close to the top of the granite intrusion and is characterized by the presence of steam filled fractures. The mapping of the H horizon (Figure 11) is thus following the top of the granitic body, that otherwise would remain undefined due to the lack of acoustic contrast between the metamorphic and intrusive rocks.

From the explorative point of view, the well observations confirm the bright-spot appearance of the H horizon, on the seismic data. The H reflection is therefore the seismic expression of steam filled fractures and is now regarded as an economically interesting exploration target.

## 5. CONCLUSIONS

The work in the Travale geothermal area shows that high-resolution seismic methods can be successfully applied to the identification of geothermal drilling targets.

An overall data consistency is essential in reducing the interpretation uncertainty and the mining risk.

In general, seismic reflections can be correlated to the information collected in wells. Some reflections result from lithological and petrophysical contrasts, while others are generated by the presence of fluid filled fractures and are direct indicators of potentially productive zones.

The high resolution reprocessing of the seismic as a single, consistent dataset has enabled a more refined and better-correlated interpretation to be made, contributing to the definition of a new geothermal model.

The deep structure of the Travale geothermal field is demonstrated by the behavior of the K and H horizons that are interpreted as expression of geological episodes of a quite recent origin.

The deep K horizon is a high amplitude reflection, likely generated by gaseous fluids concentrated in relatively thin intervals, embedded in high velocity rocks. Laterally the K horizon is cut by recent extensional and transcurrent faults, demonstrating a mechanical behaviour of elastic type.

These faults can be traced with confidence only at the level of the K horizon. Their upward extension is made difficult by the poor evidence of the overlying seismic signal. In particular, the relation with the overlying Neogene basin tectonics is still poorly known and requires further investigations.

The H horizon is shallower than the K horizon and shows bright-spot features. Well penetrations have shown it represents steam filled fractured zones near to the top of

Plio-Pleistocene intrusive bodies. The H reflection is remarkable as seismic expression of steam reservoirs potentially of high economic interest and is now regarded as a target for the deep geothermal exploration of the Travale field.

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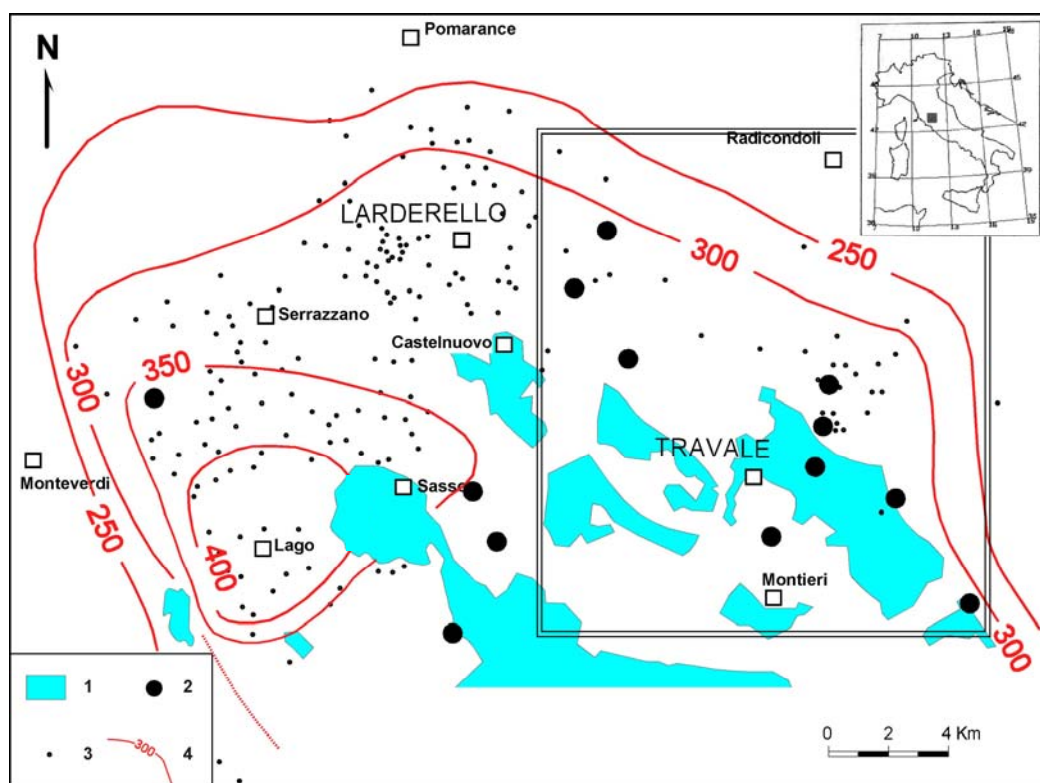


Figure 1: Temperature distribution at 3000 m b.s.l. in the Larderello – Travale Area.

1) Outcrops of shallow reservoir 2) Recent deep wells 3) Shallow wells 4) Isotherm contour lines (°C).  
The inner box shows the Travale study area.

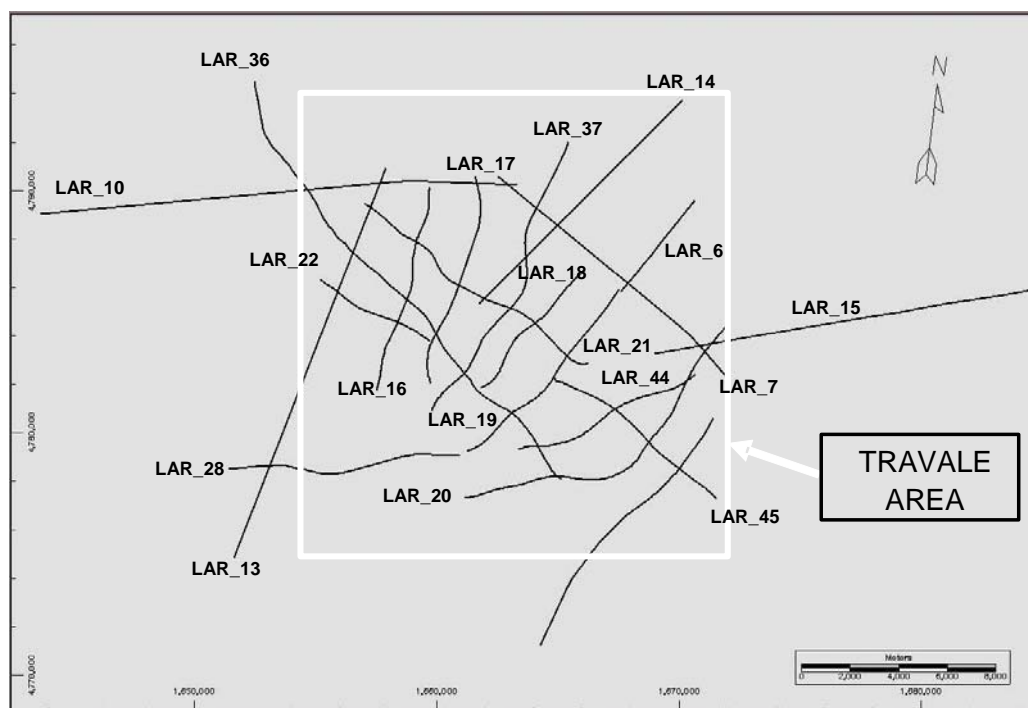
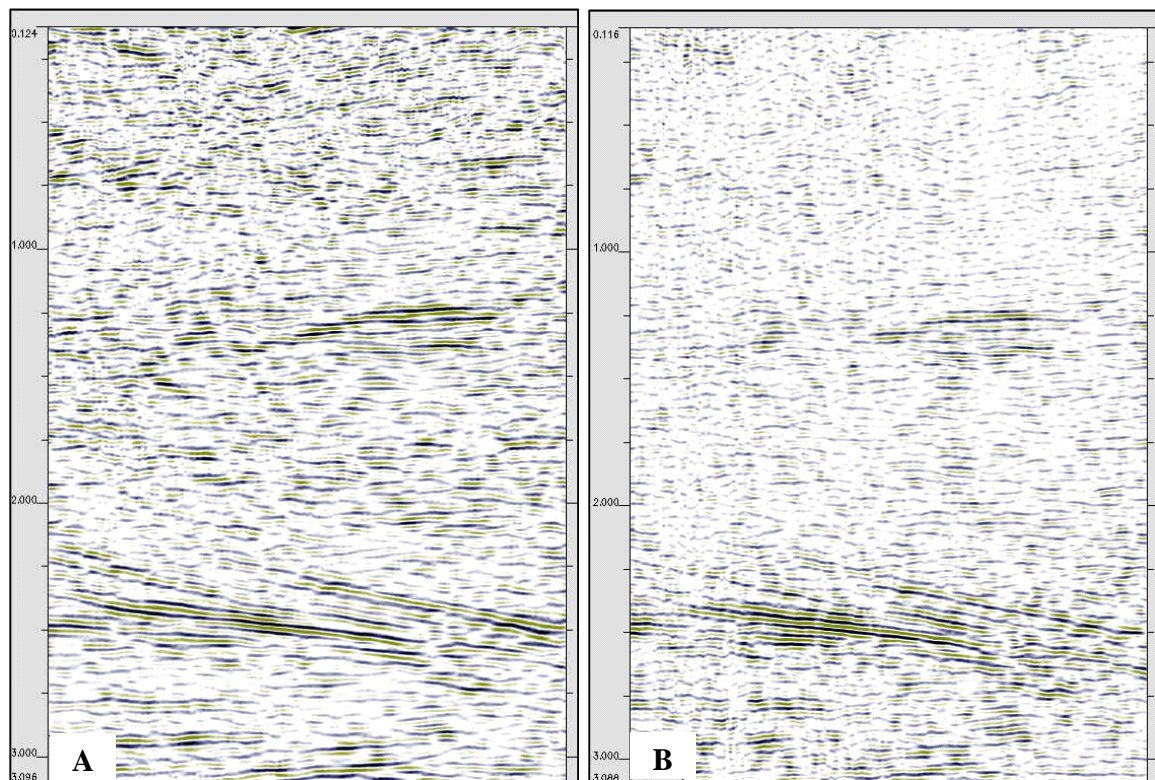
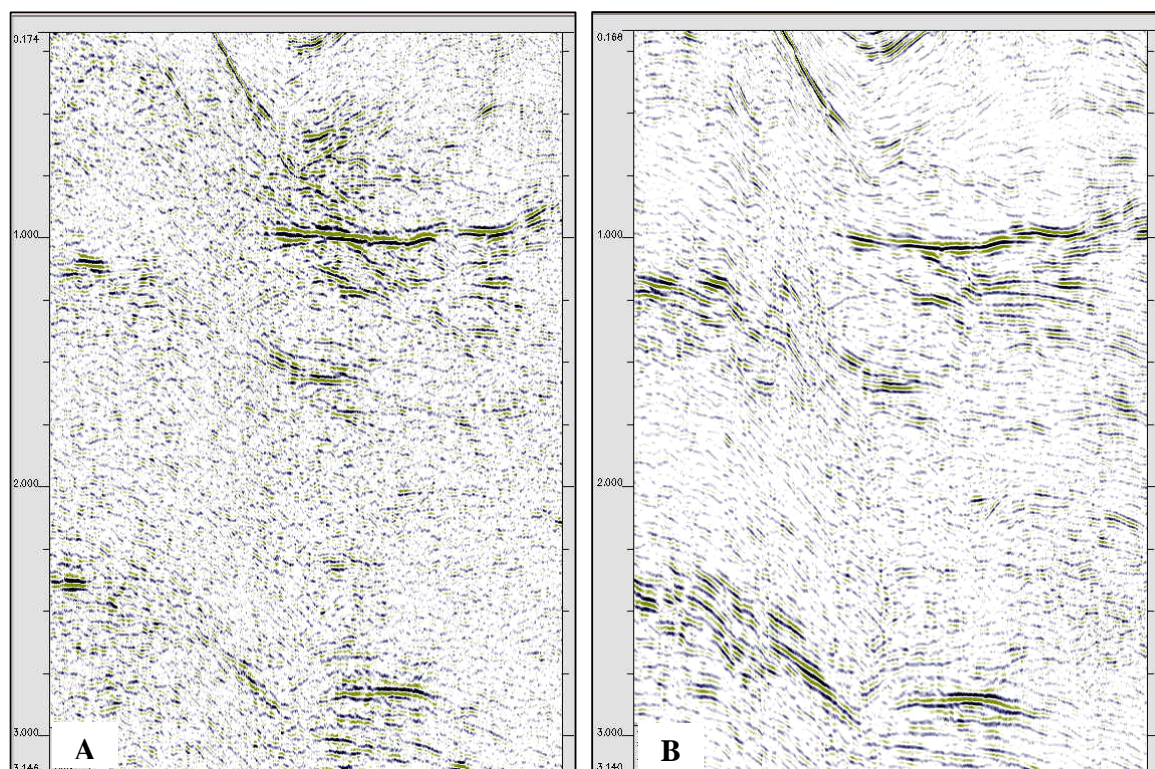


Figure 2: Location Map of 2D seismic lines in the Travale area.





**Figure 3: Seismic line Lar\_21: original (A) and reprocessed (B) Stack Section for amplitude analysis**



**Figure 4: Seismic line Lar\_37: original (A) and reprocessed (B) migrated section for structural interpretation**



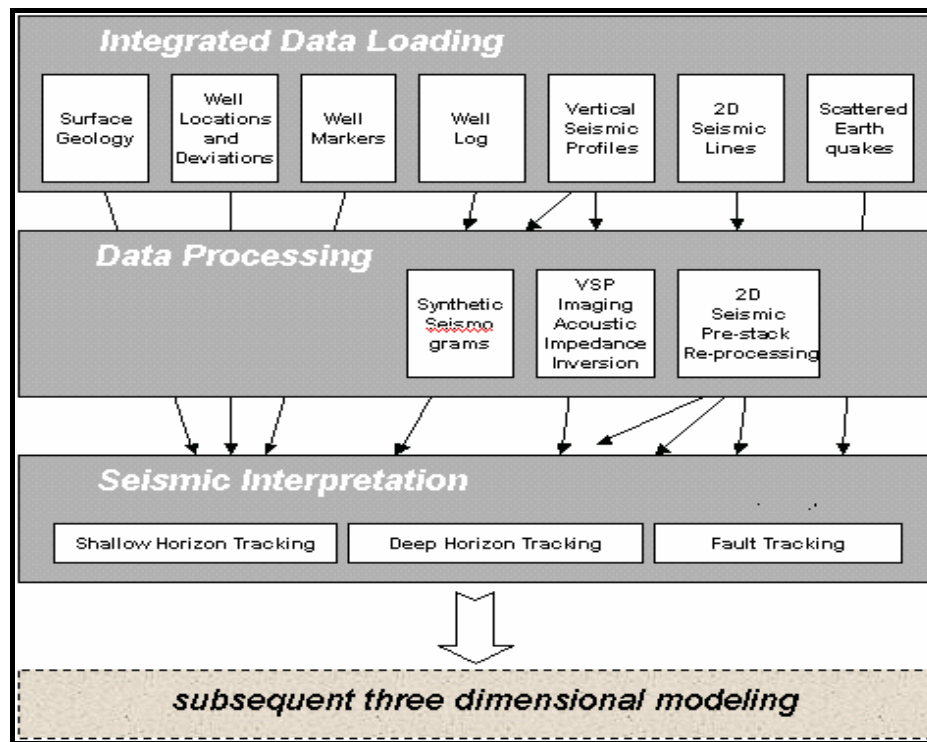


Figure 5 Workflow of data load, processing and interpretation. The subsequent modeling is described in separate paper.

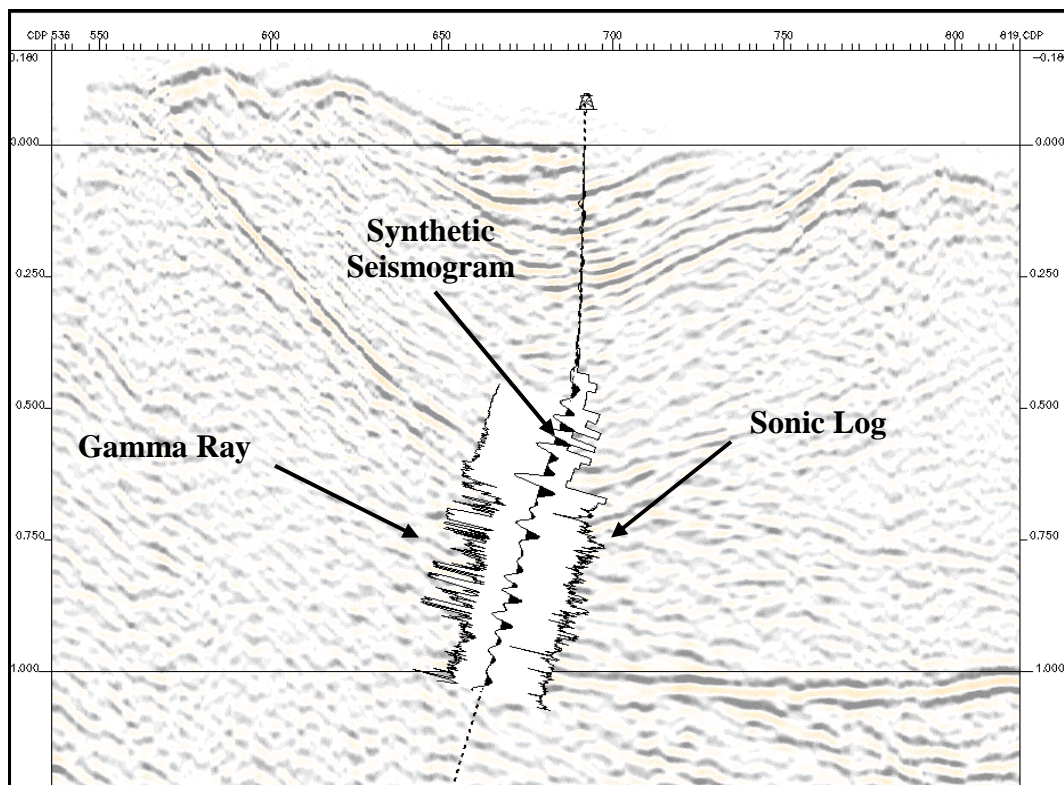


Figure 6: Example of well logs superimposed onto a seismic line. The reflection located at about 0.650 sec is created by an increase of acoustic velocity. The deep reflector at about 1 sec is not encountered by the well, thus suggesting a lateral termination.

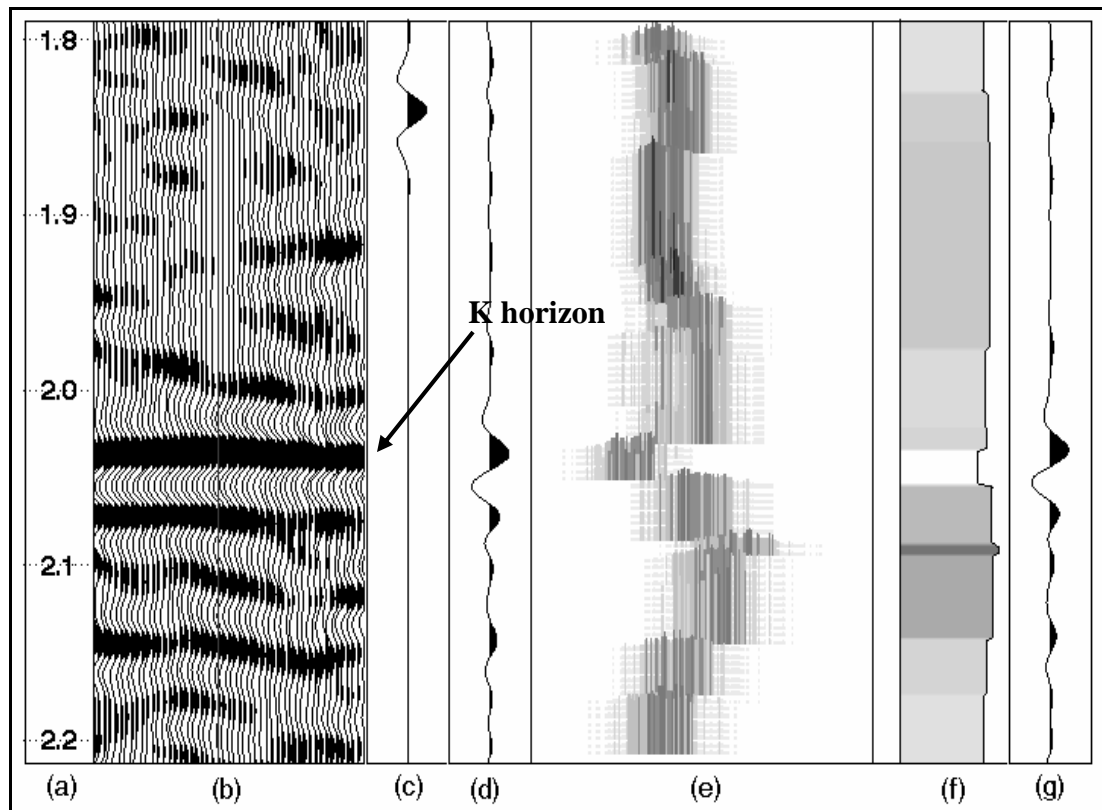


Figure 7: Example of Vertical Seismic Profile (VSP) processing and inversion: a) two way time scale b) VSP reflection traces, recorded by a geophone tool in shallow downhole positions c) seismic signature of the VSP reflections d) summary trace of the VSP reflections e) probability distribution of the inverted acoustic impedance profiles; the dark shadings indicate highly probable impedance values; the value of acoustic impedance is directly linked to rock velocity and density and, in this panel, increases to the right f) most likely profile of acoustic impedance extracted from previous panel g) synthetic trace computed from (f) and (c) for quality control.

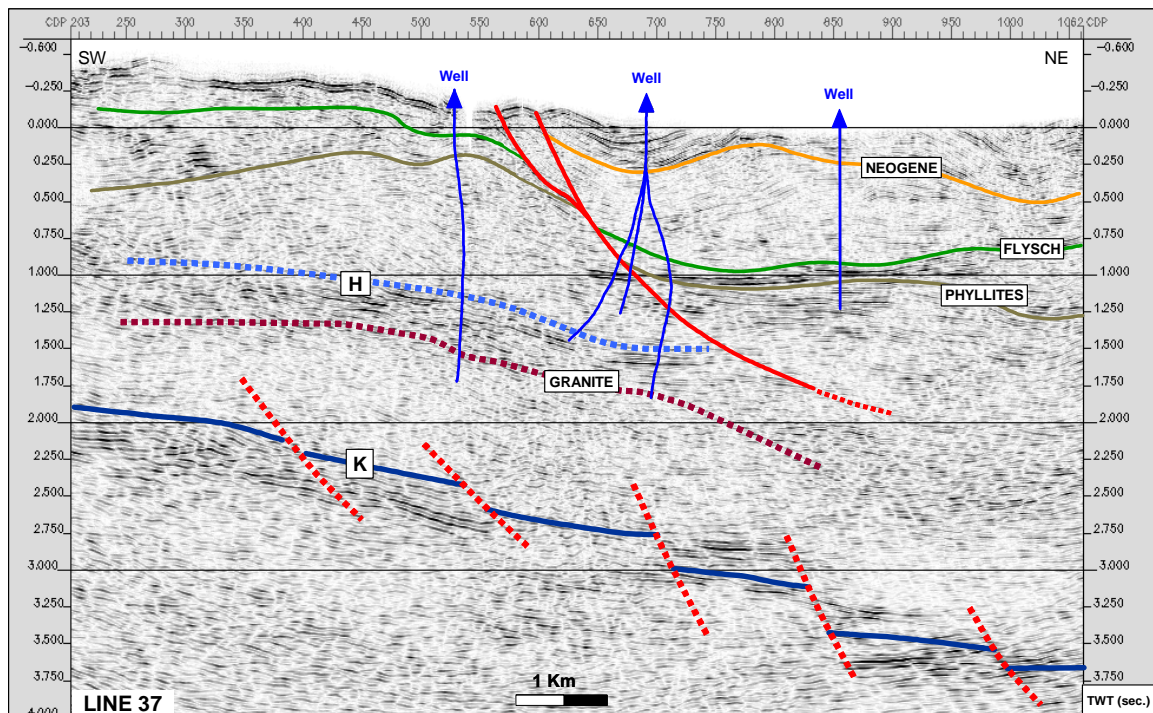


Figure 8: SW-NE reprocessed seismic line Lar-37 (migrated version) showing the main features of the structural interpretation



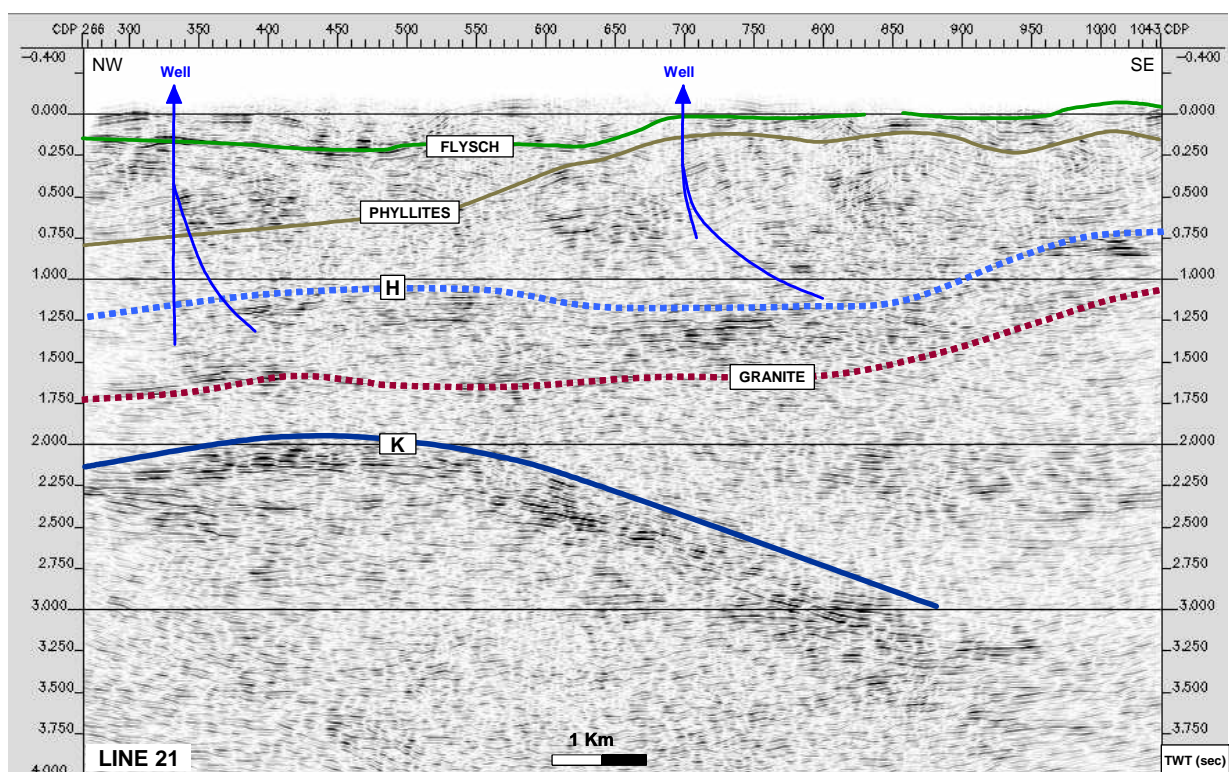


Figure 9: NW-SE reprocessed seismic line Lar-21 (migrated version) showing the main features of the structural interpretation.

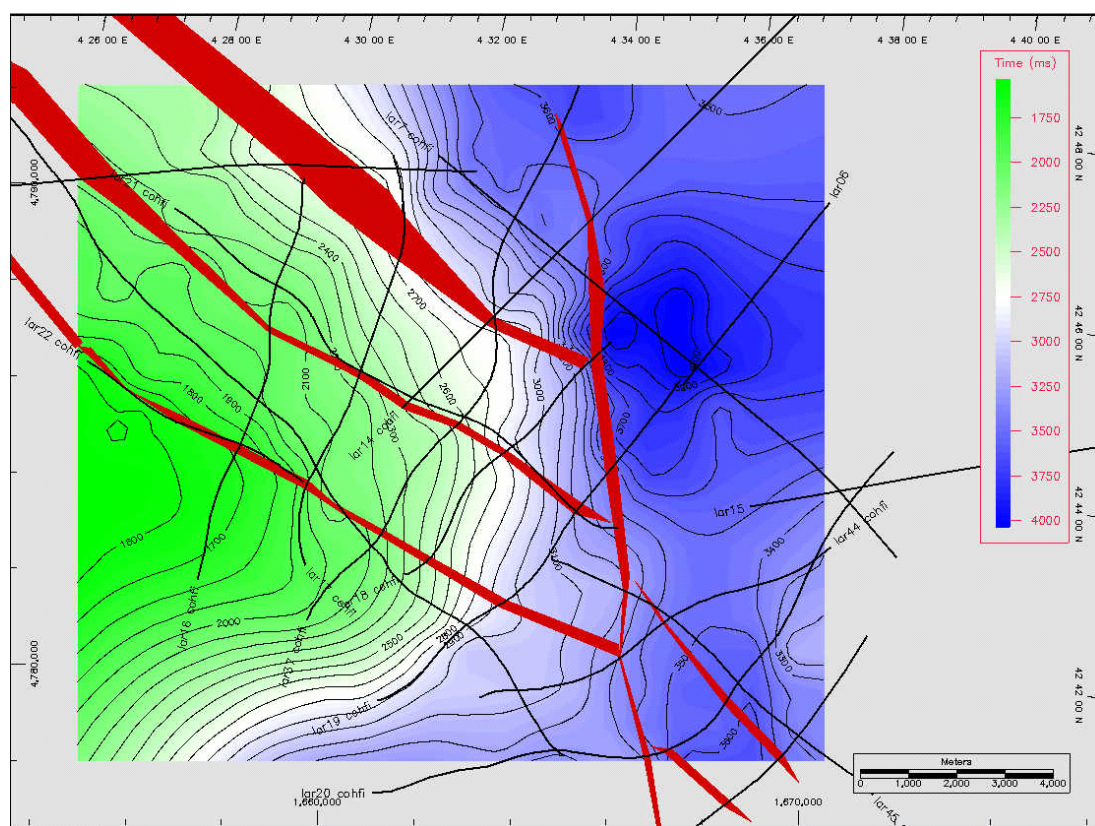


Figure 10: Map of the top of the K horizon in two-way-time, with interpreted faults and paths of the seismic lines

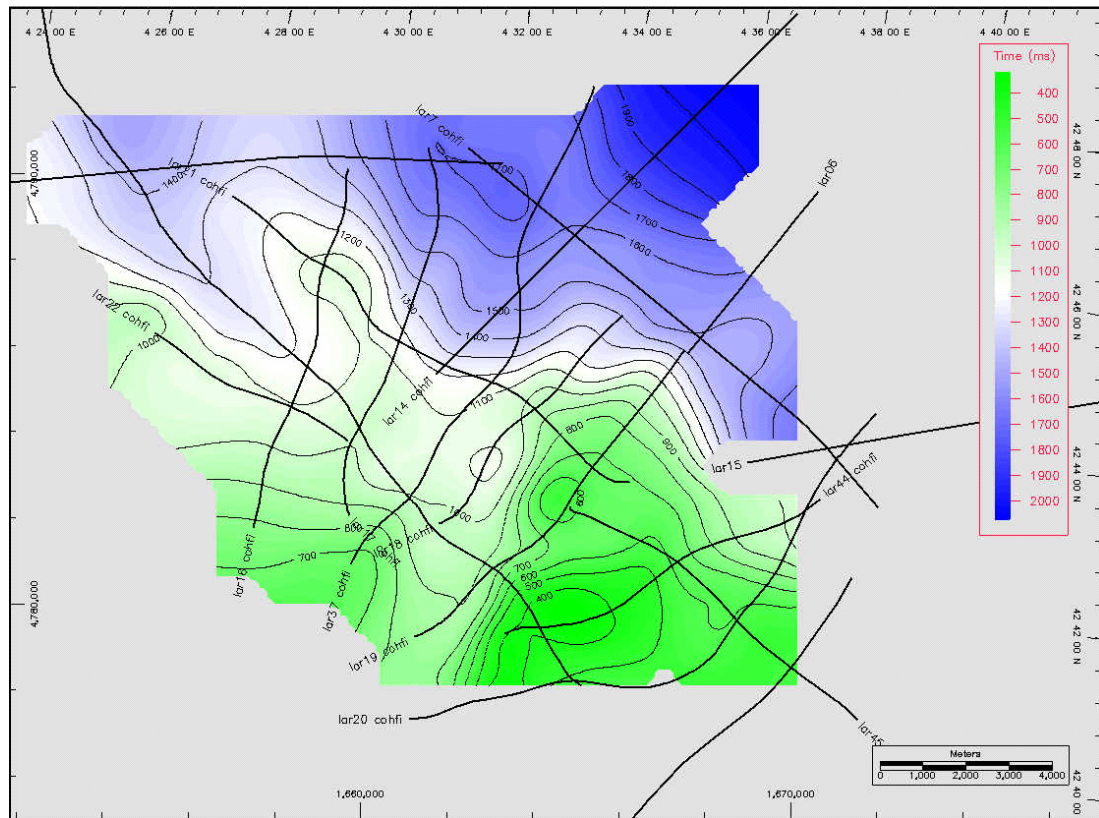


Figure 11: Map of the top of the H horizon in two-way times, with seismic line paths.