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Vertical Seismic Profile (VSP) in Injection Well AZ-03, Los Azufres Geothermal Field, México

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ABSTRACT

The application of borehole seismic technology has been developed mainly in the oil industry, but this time it has been applied in geothermal wells in order to obtain information from structural data velocities in the area surrounding the well. The development requires log as an initial step of *feasibility assessment of the acquisition* under the specific conditions of the well and the geological conditions of the area. The second step is *log design* in which the geometry is determined using the number of sensors and source parameters by using a vibro-seismic truck. The last step is the *processing and interpretation of the results*. In this case the vertical seismic profile (VSP) was run by two logs (the first *ZVSP* and second *OVSP*) in injection well AZ-03 in the geothermal field of Los Azufres. The objective was to obtain a lateral image of the well and mapping of the geological structure known as *El Chino*. The *ZVSP* log was constructed based on the model of a structural section and the measured velocities of the P wave to "illuminate" the lower sections of the well. For the *OVSP* log the source was located on the platform of the well AZ-54, obtaining an image of the north side of the injection well AZ-03, covering 500 m in the area of interest. Lateral discontinuities were identified close to the well AZ-03: between 600 m and 1350 m depth it shows that the system is northbound, from 1350 m to 1950 m depth it showed presence of fracturing, and from 2000 m to 2600 m depth it identified the fault structural system named El Chino. The results obtained indicate that the VSP log is a support in the exploration stage that identifies faults and fractures in geothermal fields in areas that lack of structural features visible on the surface. It is also an additional technique in developing geothermal conceptual models and the proposal of locations for producers and injection wells.

1. INTRODUCTION

Currently, at different geothermal fields a proper location of production and injection wells is a must, with the primary objective being the generation of electricity. Therefore, the search for new technologies such as "Vertical Seismic Profile" to complement exploration studies is a common task.

The Vertical Seismic Profile (VSP) is a technique based on the register of acoustic travel time recording the duration of the passage of a signal from the source through the Earth and back to the receiver. Also, a VSP uses the reflected energy contained in the recorded trace at each receiver position as well as the first direct path from source to receiver. The VSP use a surface seismic source, which is commonly a vibrator on land. The VSP's vary according to the design of the well, the number and location of sources and geophones. The way to get the downhole tool is wired. The VSP can be registered on condition cased or open hole wells (Figure 1).

2. VSP LOG

The VSP log is based on the measurement of first arrival of compressional waves for time versus depth values that helps to calibrate models and speeds up the process obtaining two-dimensional images of the well. The geometries which are obtained are:

- Checkshot
- Zero-Offset (ZVSP)
- Offset (OVSP)
- Walkaway VSP

This paper will focus only on two geometries Zero-Offset VSP and Offset.

2.1 Zero-Offset VSP log

Zero-Offset VSP (ZVSP): In this technique, a source is positioned at the surface near the well. Measurement of the first compressional wave arrival and later arrivals are associated with field reflected waves too. The ZVSP is acquired by an array of geophones along the wellbore with a small spacing. The spacing between stations is aim an adequate number of spatial sampling for performing the separation of wave fields; in turn it removes spatial aliasing for a maximum recovery of the range of frequencies (Figure 2).

Typically ZVSP spacing is 10, 20 or 25 m. Also a reflective seismic response of different subsurface interfaces is obtained. The reflection response of the different interfaces is a dimensional response.

2.2 Offset VSP log

Offset VSP (OVSP): In OVSP the source is away at a certain distance which reflex points are distributed in a plane and two-dimensional (2D) images are obtained in the direction of the source. In this technique, as in ZVSP the source remains fixed and the

geophones are distributed inside the wellbore (Figure 3). The lateral coverage depends on three variables: depth of objectives, detector array in the wellbore and the source distance (offset).

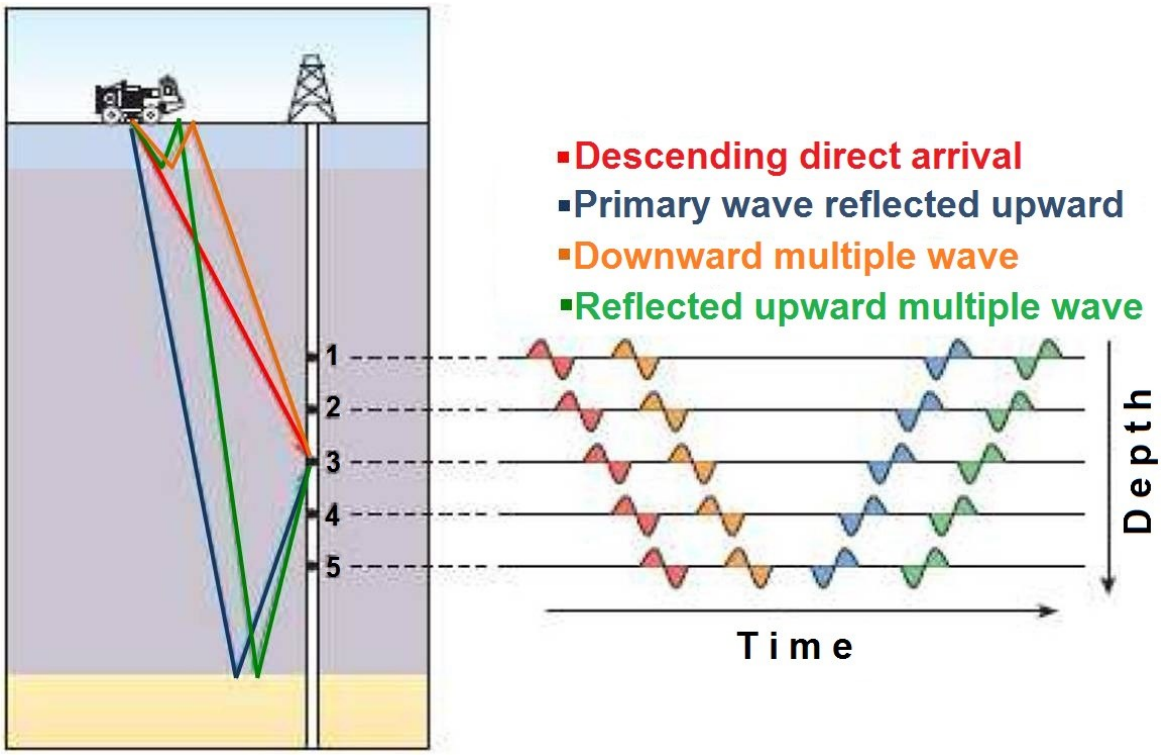

Figure 1: VSP geometry and types of generated waves (Schlumberger, 2010).

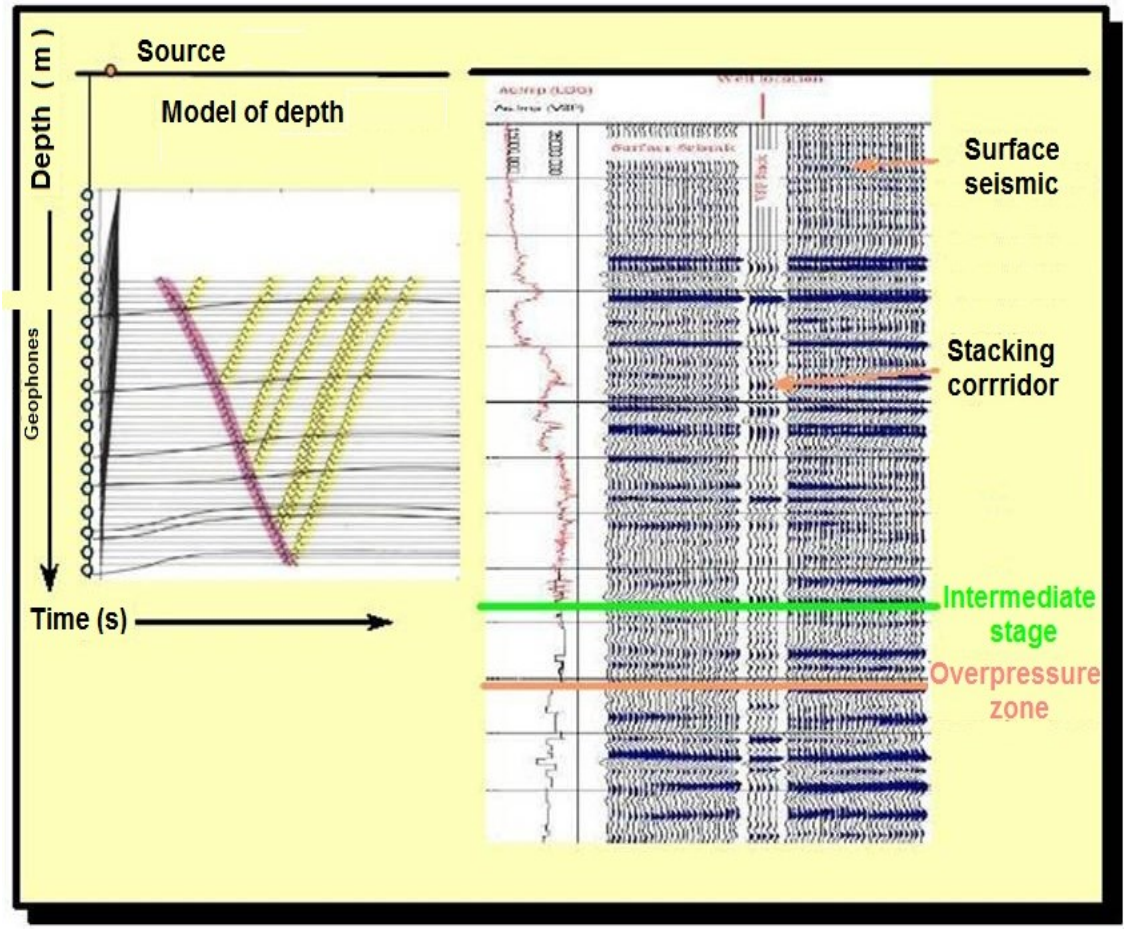

Figure 2: Zero-Offset VSP log (Schlumberger, 2010).

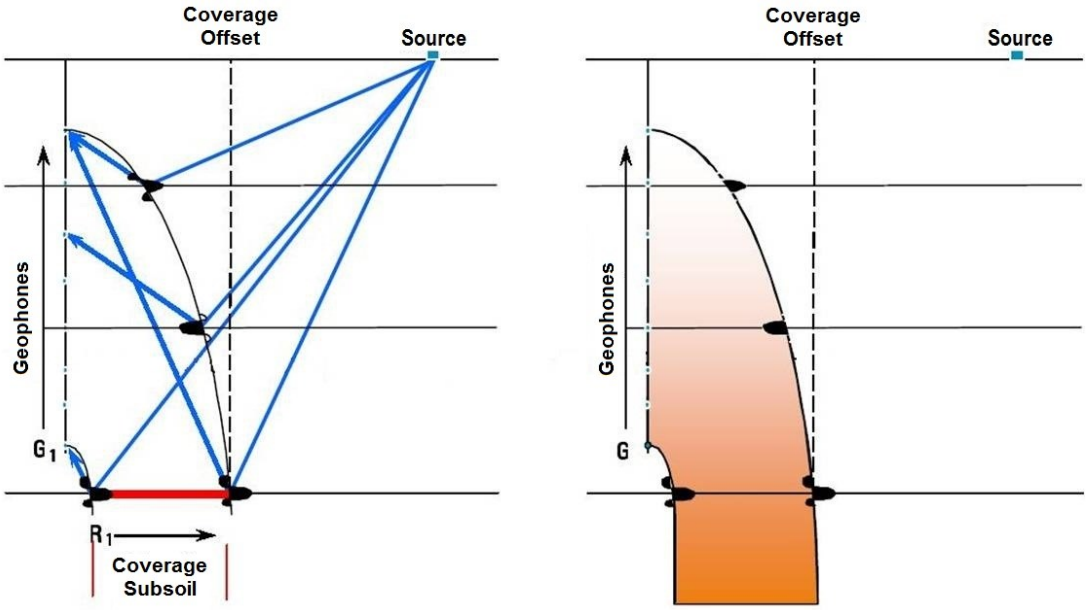

Figure 3: Offset VSP log (Schlumberger, 2010).

The application may include correlations with surface seismic data or fault identification and dip to produce images of compressional and shear wave and their velocity (Figure 4).

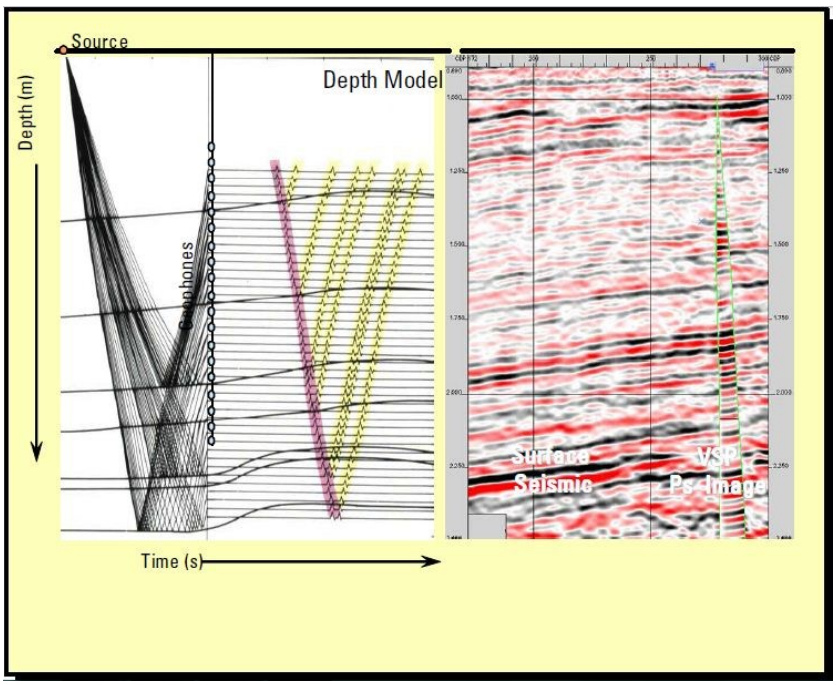

Figure 4: 2D Images of high resolution (time and depth) Schlumberger, 2010.

3. SEISMIC WELLS METODOLOGY

The log requires the development of an initial step of *feasibility assessment of the acquisition* under the specific conditions of the well and geological conditions of the area. The second step is the *design of the measurements* in which the geometry to be used, the number of geophones and the source parameters using a vibro-seismic truck is determined. The last step is the *processing and interpretation of the results*.

3.1 Assessment of the feasibility of the acquisition

The initial step of a wellbore seismic work consists in determining the acquisition parameters and the determination of the products obtained. Seismic modeling at this step is critical to determine coverage either timely or side reflectors to be enlightened with the VSP. In turn, the main point is to determine the source parameters, offset and azimuth. Seismic modeling uses a velocity model and the structural interpretation of the area surrounding the well, both the velocity model and the structural interpretation are generated in conjunction with the geophysical interpreter.

The information required for the design of seismic measurements in a vertical wellbore is:

- Existing seismic information
- Structural information of the area
- Information about seismic velocities
- The aim or problems that this survey seek to cover
- Mechanical state of the well

With this information, a technical evaluation will be performed which will help to determine the feasibility of the application of wellbore seismic profiles and the results to be obtained (Figure 5).

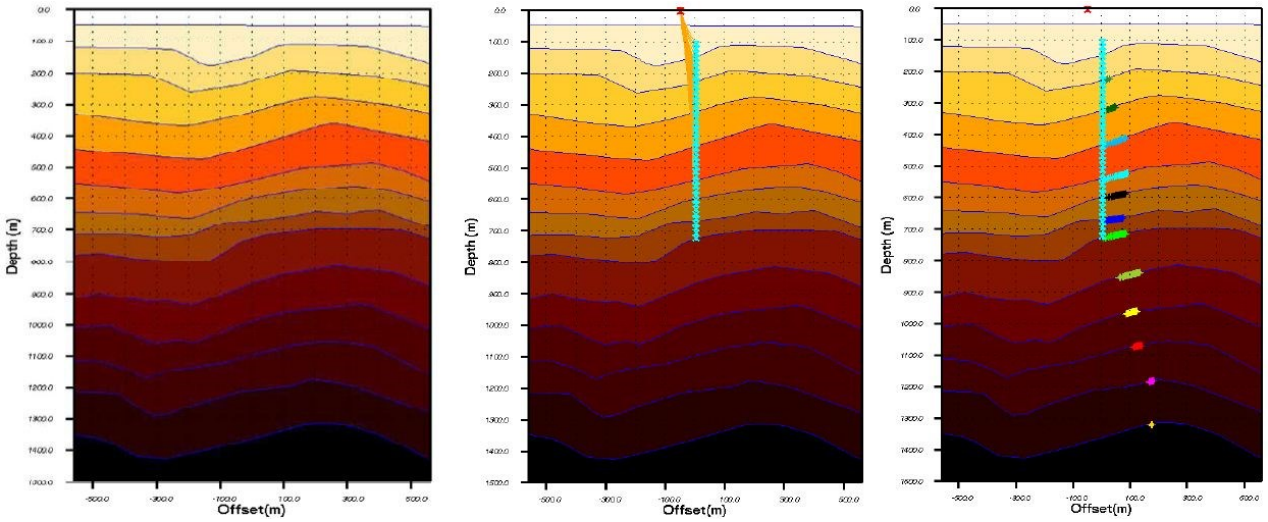

Figure 5: Modeling of velocity, P direct wave (Schlumberger, 2010).

3.2 Design of log

The next step is to review field conditions, whose aim is to ensure accessibility and optimum ground conditions. The source of energy for the surface seismic source commonly is a vibrator. Acquisition parameters are:

- Source parameters. Offset, Azimuth, number of sweeps, power, frequency and sweep time.
- Distribution of geophones in the vertical well. Distance between geophones and number of levels to acquire.
- Operational flow. Operational sequence, describing the different needs that must be met before the acquisition sequence.
- Flow data processing and quality control.
- Get results and deliverables.

4. PROCESSING AND INTERPRETATION OF RESULTS

The most important processes for VSP data are the determination of travel time first arrivals, which provide the velocity field of source-receiver direct waves, and help to build a model of velocity of high accuracy in the vicinity of the well. This relationship of time-depth will control the conversion of domain, and in turn serves for the separation and migration of the wave fields.

The next important process is the separation of the wave fields, borehole seismic waves recorded downstream fields and fields of ascending waves (reflected). The aim is to separate these wavelength fields optimally. The wave fields are also highly converted on the vertical seismic profiles and a higher resolution is needed when the source has a far offset.

Afterwards, deconvolution of the data migration is carried out to obtain the final image. For near offset (zero offset) the lateral coverage is minimal which approximates a 1D response in the case that the Offset migration provides a lateral image of specific coverage. The migration is performed in depth and time conversion is performed using the velocity model obtained from the VSP.

5. STUDY AREA

The geothermal field of Los Azufres is located in the Sierra de San Andres, on the eastern border of the State of Michoacan, 80 km to the east of the city of Morelia and 250 km from the city of Mexico (Figure 6). It sits on a volcanic complex at an elevation ranging from 2,500 to 3,000 meters above sea level. The area is mountainous and forested, currently considered Zone Forest Reserve. Due to the geological, geochemical, and reservoir production characteristics, the geothermal field of Los Azufres is divided into two areas: north and south. The southern area has the highest temperatures and the reservoir is also shallower than in the north.

An important stage for electricity generation is the exploration step and the location of producers and injection wells remains central for the location of surface and subsurface geological faults and natural fractures in situ, and through these means for the flow of geothermal fluids.

The objective of this work is to perform VSP log with geometries OVSP and ZVSP, to identify the geological structure "El Chino". The structure is located in the northern part of the geothermal field of Los Azufres, which is intercepted by injector well AZ-03. To register OVSP considered the platform of the AZ-54 well was used.

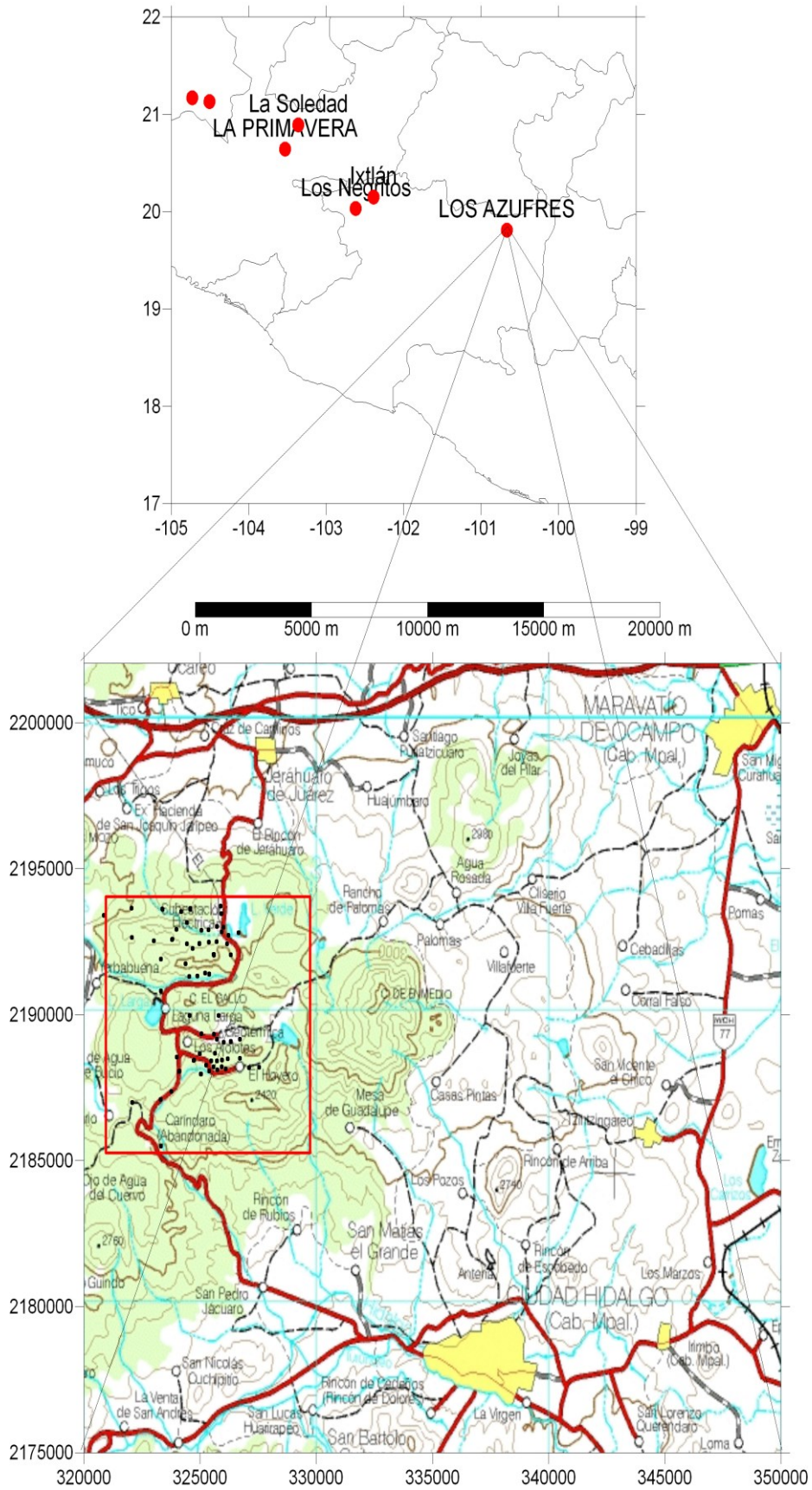

Figure 6: Location of Los Azufres geothermal field.

5.1 EVALUATION OF THE FEASIBILITY OF ACQUIRING VSP IN WELL AZ-03

The aim is to identify El Chino fault, to illuminate the area which is between 2000 to 3000m depth, the injection well AZ-03 was chosen because during its construction it intercepted a fault to 2330 m depth. The information required for designing an OVSP and ZVSP logs is:

Injection well AZ-03: Located in the northern part of the field in the vicinity of Laguna Larga, at surface 390 meters from the well the fault "El Chino" is located and intercepted to 2,330 meters depth. The mechanical design of the well is described below:

- Well Type: Vertical
- Total Depth: 2450 m
- Pipe: 9 5/8 "Liner blind up to 1400 m
- Pipe: 8 ½ "Liner blind from 1400 to 2200 m
- Pipe: 7 "Slotted Liner 2200 to 2400 m

Pressure-Temperature logs: Temperature log was taken on June 28, 2011 during warming up phase, well conditions were static, with 3 hours of repose without injection. At a depth of 2,300 m a temperature of 60°C was recorded and a maximum temperature of 70°C was recorded in the range from 900 to 1,000 m. The pressure log was taken on the same date with the same conditions in the well. It showed up pressure about 30 minutes without injecting.

Velocity data general: Comparison of data obtained with the Dipole Sonic Imager well log (DSI) with the values used in the location of seismic events, it is observed that the value currently in use Vp/Vs = 1.78, corresponding to DSI measured log. However, please note that in the range where the DSI log was made it appears that the measured P-wave velocity Vp = 4.71, differs from that used in passive seismic which is Vp = 4.0. The velocity model used is resumed in the next table:

Vp/Vs = 1.78

P wave velocity (km/s)	Depth to the bottom of the layer (km)
3.5	1.0
4.0	3.0
6.0	15.0
6.5	Halfspace

Table 1: Velocity model used for VSP.

Structural geological data: It was used in the next structural section to identify El Chino fault. The structure presents a dip of 80° (Figure 7).

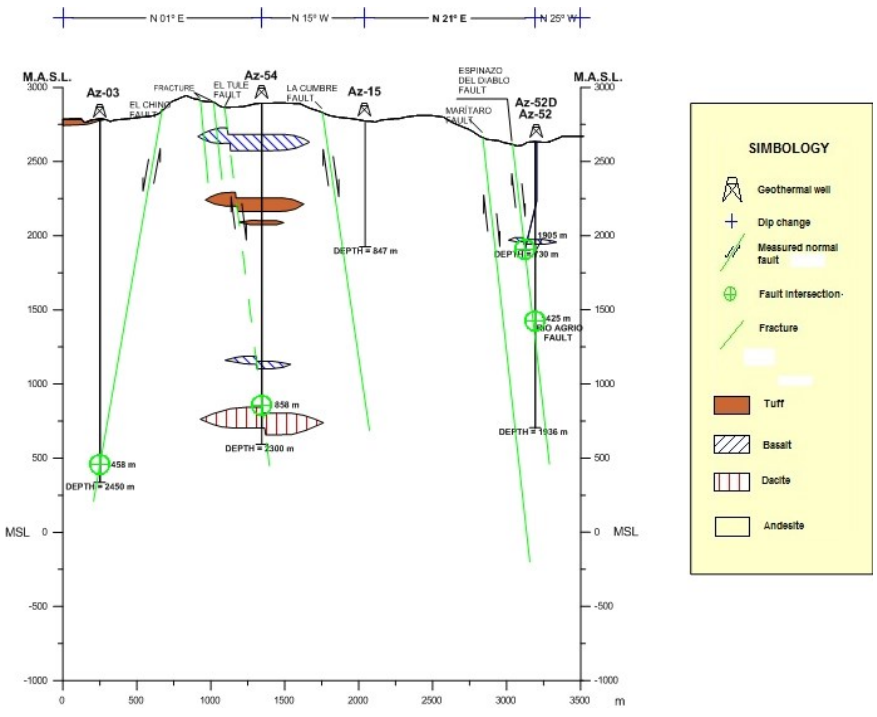

Figure 7: Structural section.

AZ-54 Well: Located north of AZ-03 injection well. Platform AZ-54 was used for OVSP log, to illuminate the area of interest in depth, same it will laterally. This will be in place through this platform power source (vibrator truck), and this energy will be detected by the geophones located into the injection well AZ-03.

5.2 Design VSP log (ZVSP and OVSP)

Figure 8 shows the locations of the geothermal wells selected for recording ZVSP and OVSP logs with the source (vibrator truck). ZVSP near to AZ-03 well and OVSP near to AZ-54 well, from this well for the lateral coverage a 2D image is obtained.

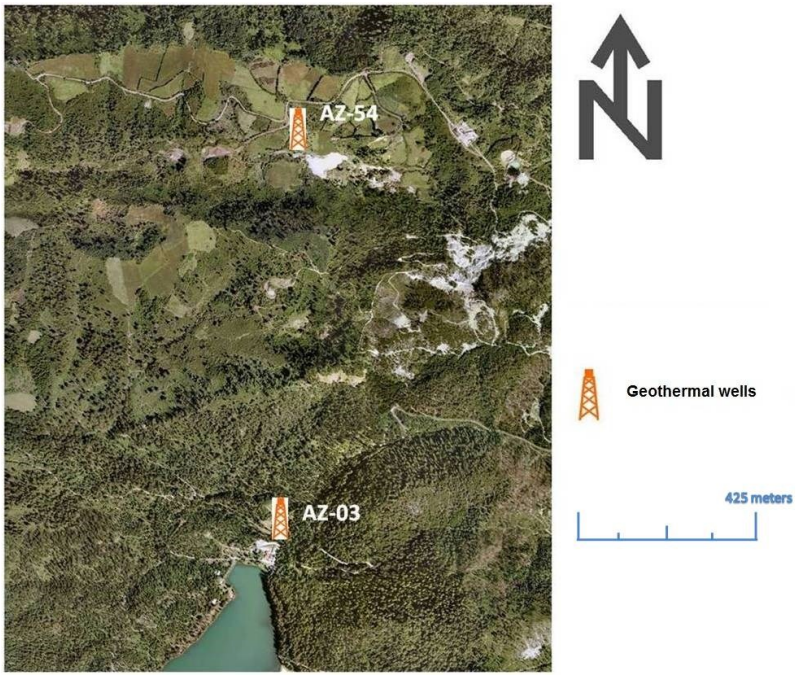

Figure 8: Location of wells AZ-03 and AZ-54.

5.2.1 Ray tracing ZVSP

Figure 9 shows how the area of interest is illuminated, which is a lateral image to the north of the injection well AZ-03. Designed coverage for this source is 200 m (lateral) in the area of interest.

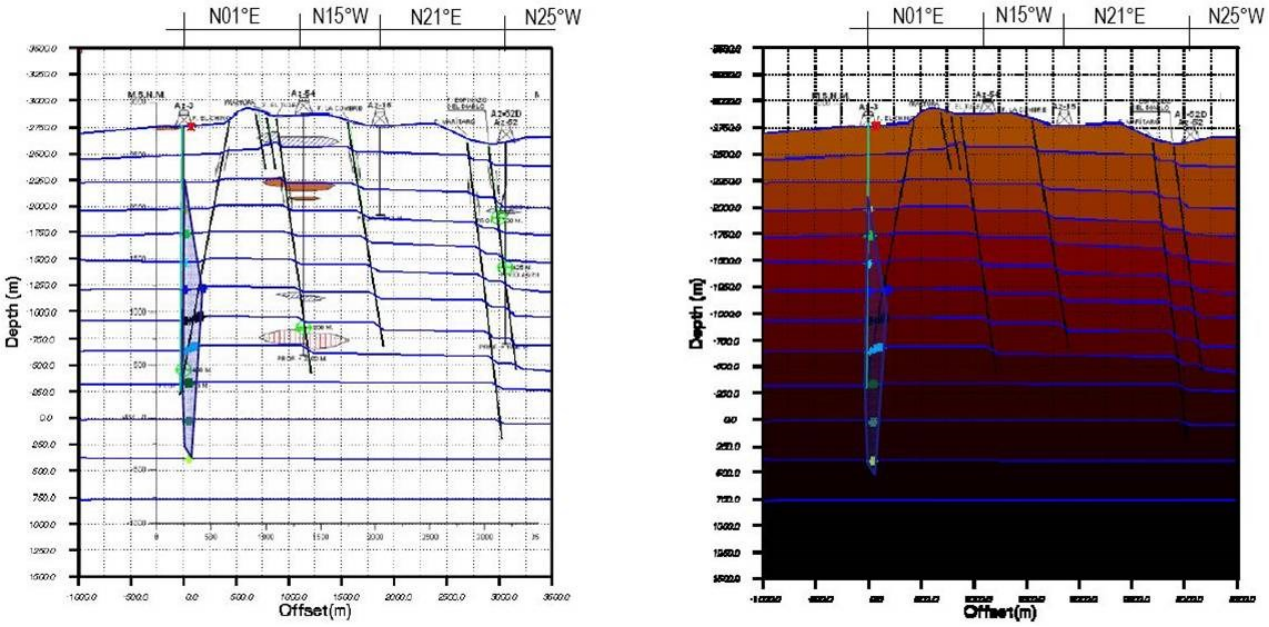

Figure 9: Design of ZVSP, shown lighting below the well (Parga, 2011).

5.2.2 Ray tracing OVSP

Figure 10 shows how the area of interest is illuminated, which is a lateral image projected to the north of the injection well AZ-03 image. Designed coverage for this source is 500 m (lateral) in the area of interest.

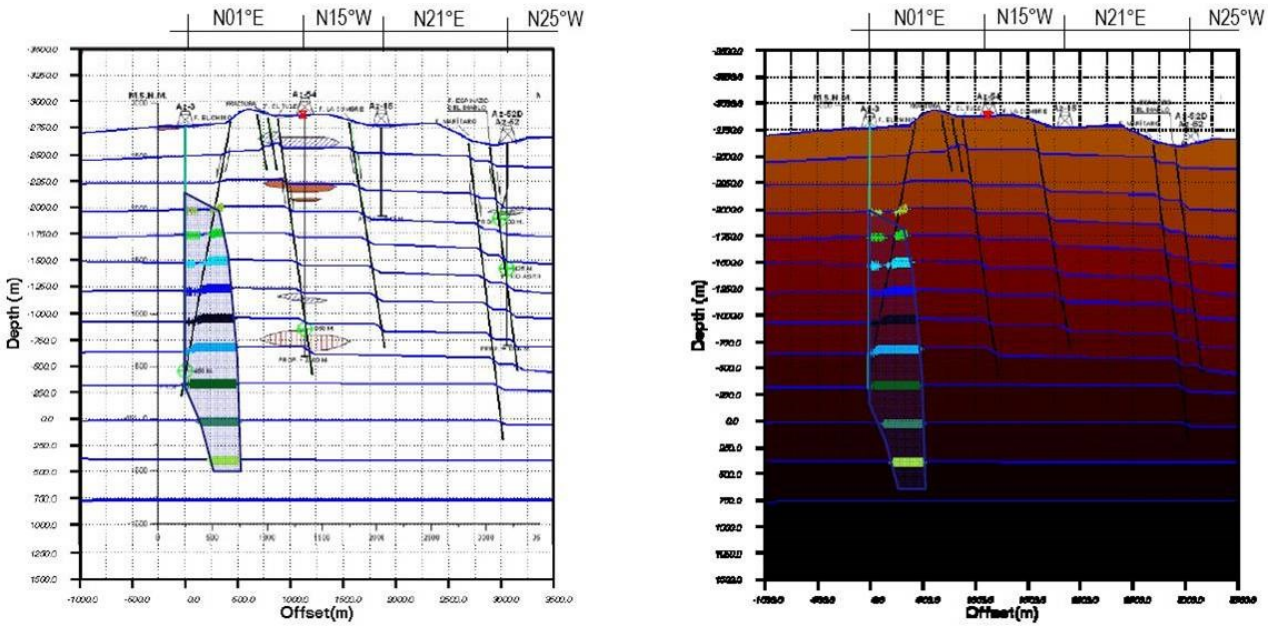

Figure 10: Design of OVSP with the source near to well AZ-54 (Parga, 2011).

5.3 Diagram for processing ZVSP and OVSP logs

Figure 11 shows the corresponding flow diagrams for each log obtained.

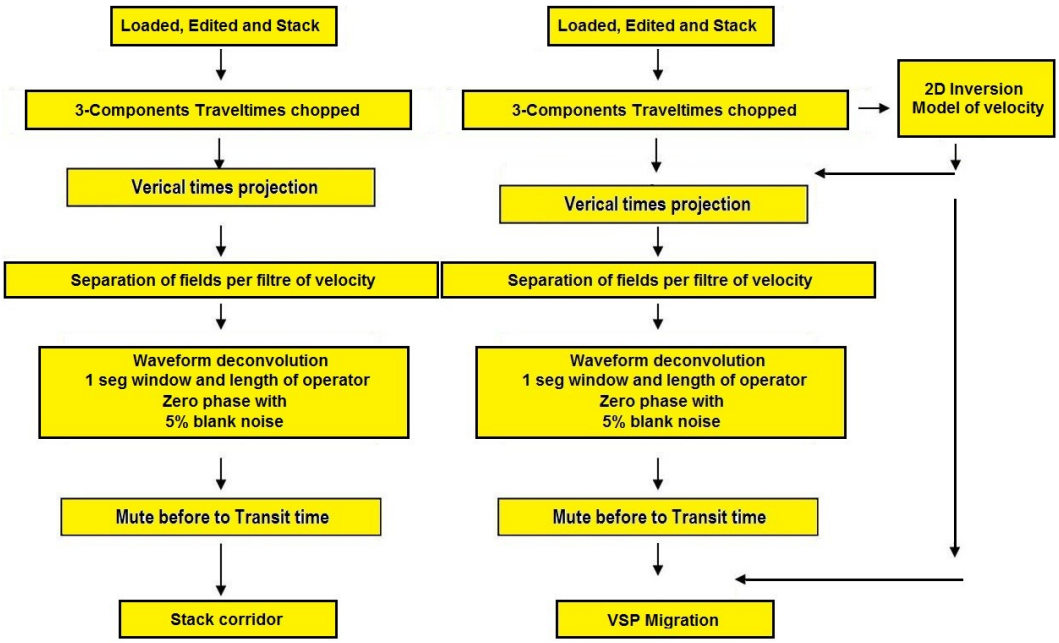

Figure 11: Flow diagrams for ZVSP (left) and OVSO (right).

After each step of the processing flow for ZVSP and OVSP logs 1D and 2D images were obtained, same images that later will be integrated into one image.

5.4 Results obtained

Identifying the first arrivals with ZVSP acquisition allowed time chopping on down waves, where it was obtained a time-depth relationship (TZ), and with it we can calculate the velocity of the medium (Figure 12).

The OVSP log achieved a lateral coverage of 500m to the north. It was possible to identify lateral discontinuities near to AZ-03 injection well. These discontinuities are interpreted as: an East system with north direction in the range of 500 to 1,350 m depth; Fracture zone in the range of 1,350 to 1,800 m depth; and identification of failure El Chino about 1,500 to 2800 m depth (Figure 12).

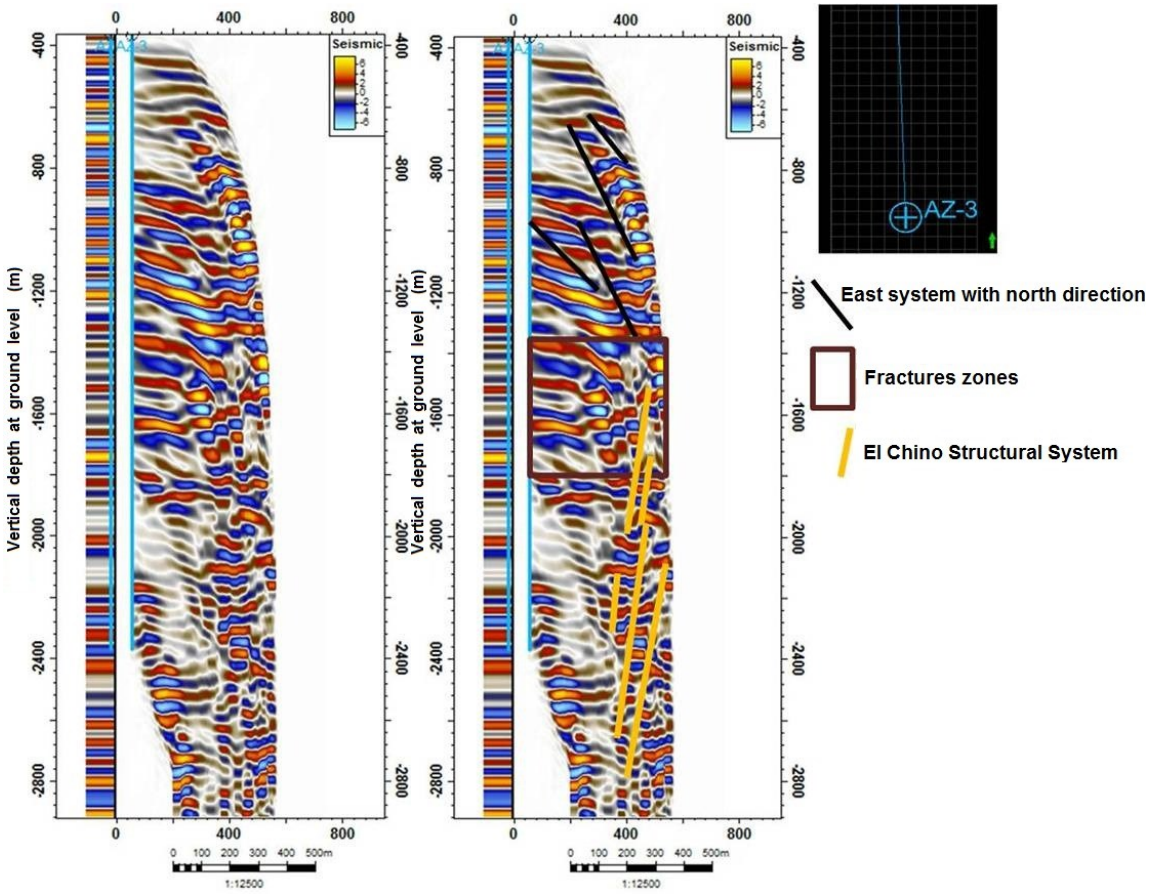

Figure 12: 1D (ZVSP) and 2D (OVSP) image (left) and interpretation of OVSP log (right).

Also, this identification was corroborated with the available information from the Reservoir Department.

A compound with the graphs obtained was performed (Figure 13), it includes data from the losses of circulation recorded during the drilling of the AZ-03 well, temperature log taken at the Az-03 well on June 28, 2011 and velocity log obtained from VSP.

Figure 13 shows that the range identified as East system in the lost circulation log during drilling had losses from 1 to 15 m^3 / h (yellow rectangle). In the range of 1,000 to 1,200 m depth also some losses were observed ranging between 9 to 15 m^3 / h (orange rectangle), which in turn is reflected by the change in velocity log (VSP velocity). This last point is also interpreted as a change of lithology at this depth. The Fracturing zone (blue rectangle) corresponds with a lost of circulation recorded with losses of around 5 and 16 m^3 / h in the interval between 1,400 to 1,850 m depth and a temperature increase until 60 °C. Finally the Fault El Chino is observed in the 2D image from 1,500 m to 2,800 m depth. It was the place that was brighter, although the AZ-03 well was ended at a depth of 2,440 m, it can be seen that a greater lost of circulation is occurring at the bottom of well, around 60 m^3 / h, and the intercepted depth to that fault was reported in the well to 2300 m deep.

6. CONCLUSION

Identification of lateral discontinuities near injection well AZ-03:

- East system with north direction in the range of 500 m to 1,350 m depth
- Fracture zone in the range of 1,350 m to 1,800 m depth
- Identifying El Chino fault aprox. at 1,500 m to 2,800 m depth

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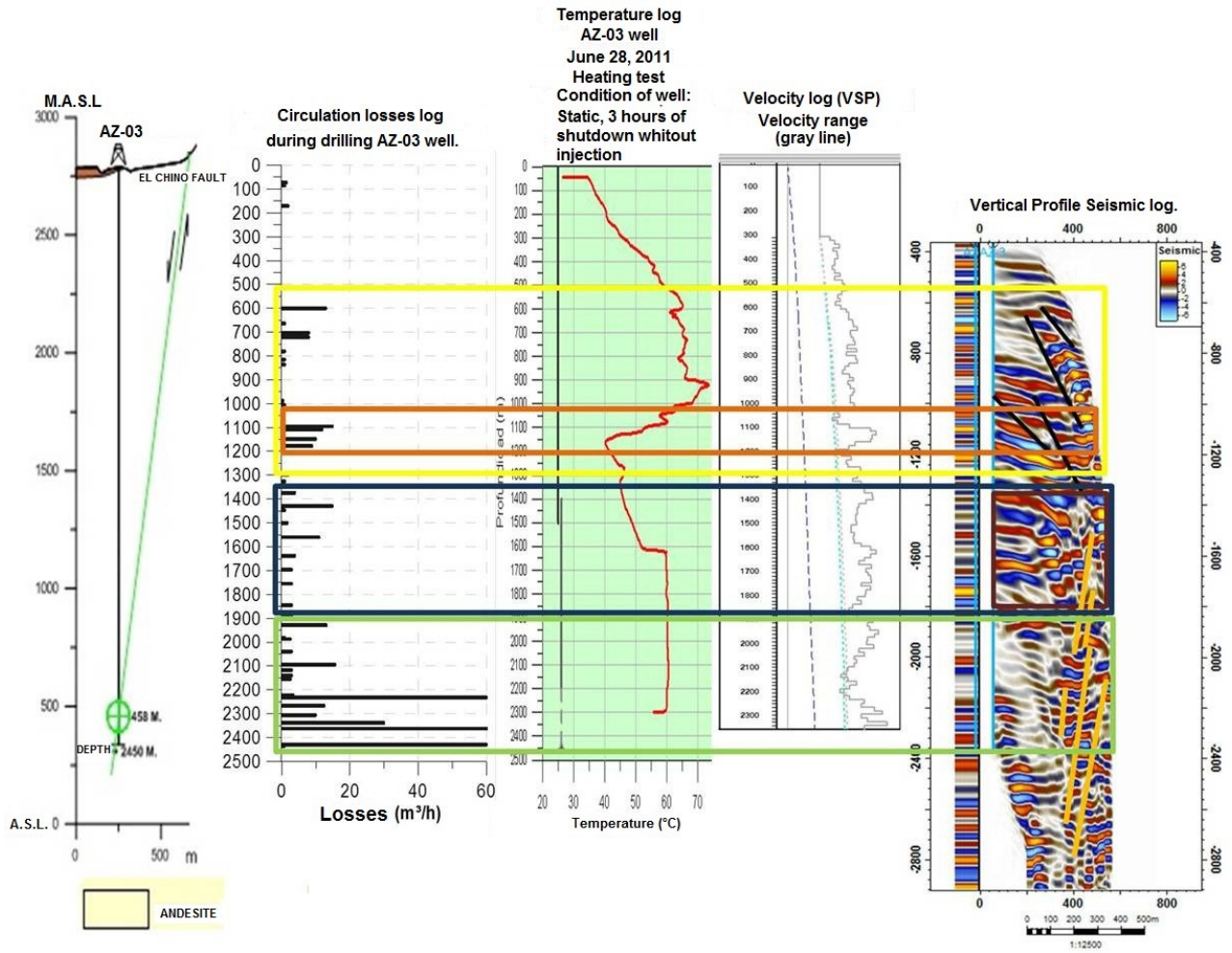

Figure 13: Composite Image.

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