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Application of Spontaneous Potential in the Geothermal Area of La Soledad, México

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ABSTRACT

The Comisión Federal de Electricidad (CFE) through the Geothermal Projects Management (GPG), evaluates the energy potential of the heat sources of the Mexican Republic, in geothermal areas currently allowed for CFE by the Secretary of Energy (SENER). The objective is to contribute to the coverage of the growing demand in the supply of electrical energy through the development of new generation geothermal fields.

The complementary technique called spontaneous potential (SP) was applied for the first time in the exploration of geothermal areas in Mexico. In this article we present the results of its application in the geothermal area of La Soledad, Jalisco. The results of the application of the technique allowed for discovering the existence of an anomaly of SP towards the Southeast (SE) of the geothermal area of La Soledad (up to 185 mV) between the towns of Huaxtla and San Lorenzo, with a tendency NE-SW. The anomaly is related to areas of high permeability and hydrothermal systems by the correlation with the geochemical information and electrical resistivity. Five earthquakes were recorded that were located East (E) of Huilotán and San Lorenzo (approximately 1 km), with depths between 3 and 3.5 km. The seismicity defines a fault plane in the WNW-ESE direction that matches the active fault system of La Soledad. This fault plane limits the North with the SP anomaly and probably conducts the geothermal fluids of the place. According to the SP anomaly and low S wave velocity, the local seismicity registered in the area, and the correlation with the geochemical information and the electrical resistivity anomalies, an area of probable geothermal potential was delimited with an area of approximately 5 km^2 to the SE of the geothermal area of La Soledad in the surroundings of the town of Huaxtla. It is noted that the area of possible greater geothermal potential extends to the South outside the area delimited for this study, due to what was observed in the anomaly of Poisson's coefficient.

The applied methodology of SP, and the use of already known techniques for the corroboration of results, such as the analysis of local seismicity, were ideal to define and delimit the extension of the hydrothermal system in the geothermal area of La Soledad. They were also useful to identify the active fault system of the region, by which fluids probably ascended and cause the thermal springs of the area and the observed electrical resistivity anomalies.

1. INTRODUCTION

The Commisión Federal de Electricidad (CFE) through the Geothermal Projects Management (GPG), evaluates the energy potential of the heat sources of the Mexican Republic, in geothermal areas currently allowed for CFE by the Secretary of Energy (SENER). The above, aims to contribute to the growing demand in the supply of electrical energy through the development of new generation geothermal fields. The GPG first used the implementation of new complementary geophysical methods in exploration of geothermal areas, e.g., the spontaneous potential, soil gas, and thermal and seismic tomography. This article presents the results of the application of spontaneous potential (SP) in the geothermal area of La Soledad, Mexico.

The geothermal area La Soledad is located in the State of Jalisco, Mexico. It is located 75 km in a straight line to the West of the city of Guadalajara, between the municipalities of Zapopan and San Cristóbal de la Barranca. The location is at coordinates X = 668818, Y = 2317188, and Z = 867 m.a.s.l. (Figure 1). It is a rectangular area of about 12 x 7.5 km, with an area of 90 km^2. The main access to the area is by federal highway, Tesistán-San Cristóbal la Barranca, which crosses the area of exploration from South to North.

The geothermal area of La Soledad is a hydrothermal discharge aligned NW-SE. It behaves like a tabular body and covers an approximate area of 150 m^2. It is located within the province of the Western Sierra Madre Occidental. In the base surface rocks Andesite Pre-Sierra Madre Occidental (Oligocene-Miocene), and outcrops rocks Ignimbrites and Rhyolites (Pliocene) of the volcanic province Sierra Madre Occidental. Morphologically there is abrupt topography (Figure 2). The present geohydrology of hydrological Region no. 12, which includes the basin of the Río Grande de Santiago, has apparently hydrothermal discharge due to the failure of La Soledad. The main structure that controls the spas in the area presents an orientation NW-SE, NE-SW, and NS being these conductive structures. Hydrothermal alteration is observed on the surface using warm springs, and only one hot spring on the margins of the Río Santiago. The springs range in temperatures of 35 - 37° C and 80° C with a pH of 5-7. The flow of the thermal fluid (22 water samples for chemical analysis), is estimated to reach 0.1 l/s. The lithology which emanates rocks is andesitic Pre-Sierra Madre Occidental, which looks compact with facies brecciated and having a vesicular structure. It is characterized by vesicles precipitation of calcite (Jimenez Salgado et al., 2017).

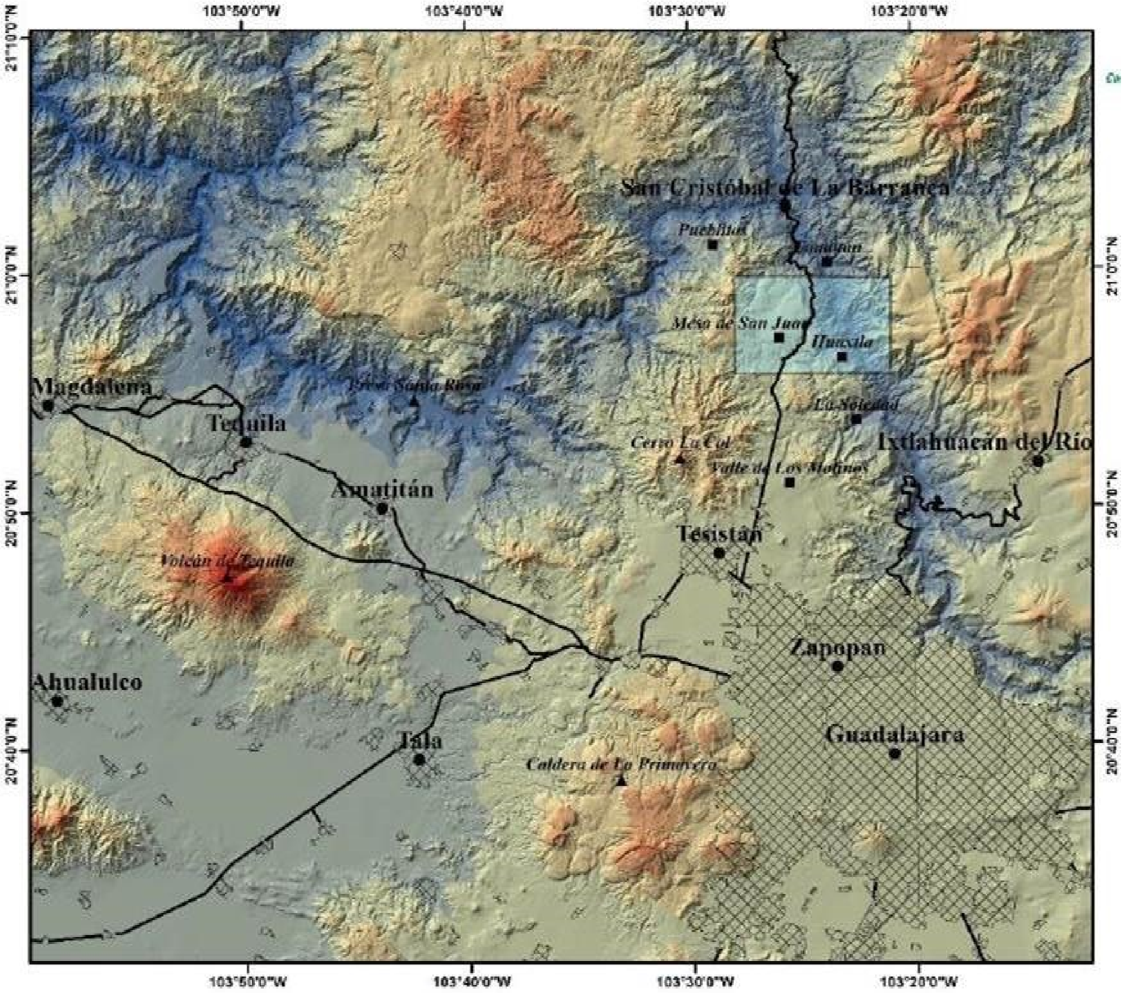

Figure 1: Location of the La Soledad geothermal area (blue rectangle).

Figure 2: Panoramic view of the La Soledad geothermal area.

2. PREVIOUS STUDIES OF EXPLORATION

2.1 Local Tectonic Setting

According to the Department of Exploration of CFE (1990), in the area were three structural systems, two of which probably originated from the late Miocene or early Pliocene (one of which was re-activated in the Quaternary), and one older Quaternary. The old systems are NW-SE and NE-SW. The first includes the important normal fault through which the Río Grande de Santiago flows in the study area, considering that it has a late Miocene age; their fallen blocks are to the NE and the structures of this system mainly affect the lithological unit of Oligo-Miocene age. The NE-SW system, for its part, although it appears to have also originated from the late Miocene or early Pliocene, it is evident that has been reactivated during the Quaternary period, because that cuts rocks of this age, and eventually moved to a fault belonging to the NW-SE system. To the NE-SW system belongs the failure La Soledad, which seems to be a structure of basement. It formed in the Mio-Pliocene, acted as fracture without movement of blocks, but was reactivated in the Quaternary becoming a failure. This failure of La Soledad, and in general the structures of this system, act as conduits of geothermal fluids to the surface and, thus, control the presence of thermal manifestations. The most recent, also Quaternary system has a nearly East-West direction (WNW - ESE), having found small structures belonging to it affecting the Quaternary rhyolites of the dome called El Chicharrón, among others. This system is very little developed in the area. They have very small size structures, and are considered to have been produced by extensional tectonics, probably related to the formation of the Chapala graben (Department of Exploration, 1990). Apart from structural and geological studies made by the CFE, there are few works that describe systems failures in the area of La Soledad or the surrounding area. Rossotti et al. (2002), Spinnler et al. (2000) and Moore et al. (1994) describe some of the systems failures and guidelines of this site in general.

Rossotti et al. (2002) describe one lineament with a NNW trend observed for at least 40 km from Guadalajara to San Cristóbal de la Barranca (Figure 3). This alignment is not understood clearly since geological and seismic data give apparently conflicting results. A possible normal fault can be inferred because the historical seismicity coincides with a great line segment marked on the Río Santiago. In fact, some landslides, probably Holocene, have been observed along the Canyon of the Río Santiago. In addition, the town of San Cristobal de Barranca was almost completely destroyed in 1875 due to an earthquake. In contrast, although the limit of the Rhyolite of the Espinazo del Diablo is in the trace of the inferred fault, no fault planes were observed in these rocks or in the San Cristóbal tuff. It is concluded that the fault may be an old feature reactivated in recent times. The failure to find the current fault planes may be due to the unconsolidated river deposits of the Río Santiago, which cover the area of the inferred fault. Spinnler et al. (2000) recognized an E-W structure defined by the alignment of the canyons of the Rio Grande de Santiago and the Río Juchipila near San Cristóbal de la Barranca (Figure 3). The alignment of San Cristobal is evident morphologically since it causes the deviation of the two rivers and controls its course for several kilometers. They also suggest the presence of an important normal fault towards NW-SE which controls the course of the Río Grande de Santiago from Guadalajara and San Cristobal in the Northern part with the lineament. Moore et al. (1994) mentions that the San Cristóbal basalts seem to have been developed in a basin limited by faults that have as limit to the North the oldest ash flows of the SMO. Normal faults on a small scale have been found within the San Cristobal stream. These failures have an approximate N-S trend, with displacement of 200 to 300 m.

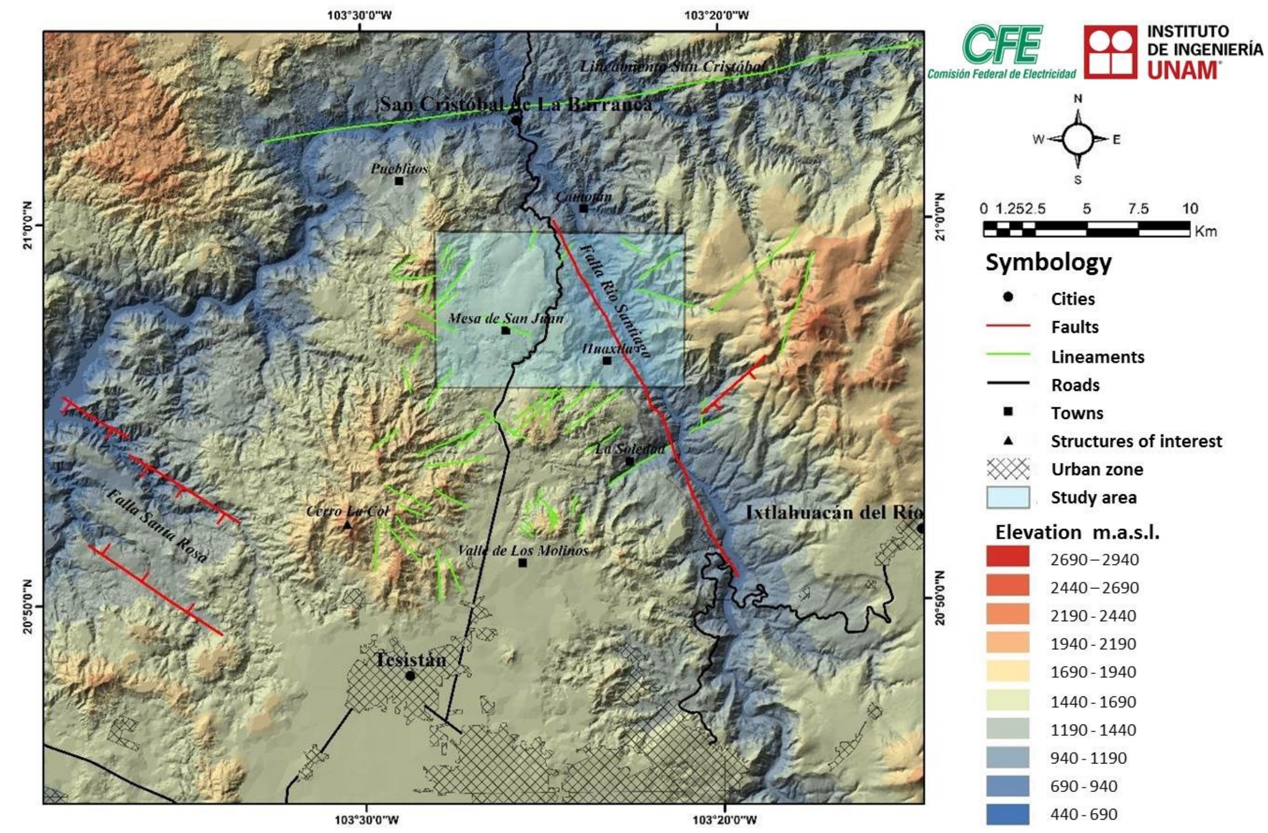

Figure 3: Map of faults in the geothermal area of La Soledad. The lineaments were taken from the F13-D55 letter scale 1: 50,000 from the National Institute of Statistics and Geography (INEGI by its name in Spanish: Instituto Nacional de Estadística y Geografía).

2.2 Local Geology

Geological exploration by CFE in 1990 describes that in the area there are only rocks of volcanic origin, which were grouped into eleven lithologic units. The basal and oldest unit is an andesite with intercalations basalt at its base, and sporadic horizons of ignimbrites at its top of oligo-Miocene age. This is located on both margins of the Río Grande de Santiago, from its bed - at an elevation of 855 m.a.s.l.-up to one elevation of 1300 m.a.s.l., which implies a minimum thickness of 445 m. This unit overlays the rhyolitical complex of the Sierra de San Francisco (rhyolites, ignimbrites and vitrof) of Miocene age, which overlays a nearly continuous series of rocks of acid character, represented by various types of pyroclastics and rhyolites, then as basic character, represented by basalts and breccias of the late Pliocene. On the left margin of the Río Grande de Santiago, corresponding to the Mexican Volcanic Belt, above rocks are covered by domes and spills plio-Quaternary and Quaternary rhyolitic. Locally, there is a small outcrop of a conglomerate, probably of fluvial origin, composed of rhyolitic and ignimbritic fragments of quaternary age. It can be observed that in the mentioned margin the volcanic activity has been very continuous in time, giving rise to tables and dummy bodies, some of which have been reactivated, producing extensive rhyolitic spills that flowed erratically from common eruptive centers, as well as Fissural spills of basalts represented by plateaus of scarce extension and thickness. In contrast, on the right margin of the river, in the domain corresponding to the Sierra Madre Occidental (SMO), volcanic activity has been mainly basic to intermediate, although it has probably extended in time to the Quaternary. The most recent acid volcanism occurs in the portion of the Mexican Volcanic Belt (MVB), and its products include the Jacal de Piedra rhyolitic dome, of Plio-Quaternary age, the El Chicharrón dome, of quaternary age, and two rhyolitic spills of the Jacal de Piedra itself (one to the East and one to the West) that are considered to be the last volcanic events in the area. It should be added that the aforementioned recent acidic spills and domes tend to be located in a NW-SE structural corridor, considered as a zone of weakness delimited by two identifiable fractures in aerial photographs (Department of Exploration, 1990).

2.2.1 Surface Geology

La Soledad is located on the boundary between the MVB and the SMO, with the Rio Grande de Santiago acting as a border. In the portion corresponding to the SMO (right margin of the river) the volcanism has been of intermediate to basic type. In contrast, in the part belonging to the MVB (left margin of the river) the volcanism presents quaternary rhyolitic products.

2.2.2 Structural Geology

Three structural systems were identified in the area, of which the NE-SW direction shows evidence of quaternary reactivations. The La Soledad fault (belonging to this system) is the main conductor of geothermal fluids towards the surface. This NE-SW system is, therefore, the most important from the geothermal point of view. The NW-SE system is older, despite its regional dimensions, and the WNW-ESE system, despite its youth, is still very underdeveloped in the zone.

2.2.3 Hydrothermal and Hydrothermal Alterations

Most of the high temperature thermal manifestations are located on the right bank of the La Soledad stream, which takes advantage of the fault of the same name to discharge its waters to the Rio Grande de Santiago. The demonstrations consist of hot water springs, some with steam and gases, that appear concentrated in several areas of La Soledad. Most of the springs lack zones of hydrothermal alteration, except those that are in the margin of the stream of La Soledad in the lower block of the fault of the same name. Here, over a kilometer, it is possible to observe abundant deposits of calcite, travertine, clay minerals, oxides, chlorite and amorphous silica, minerals that fill small fractures and that, in some cases, replace almost completely the original andesitic unit.

2.3 Geochemistry

2.3.1 Chemical Characteristics of Water

The springs in the La Soledad area are classified into two main geochemical groups. The first is the sodium sulphated type. The springs that recorded the highest surface temperatures in the area of La Soledad El Vado and Pedazo Grande belong to it. The second group is mixed bicarbonated type, varying from sodium to magnesian calcium. The spring of La Calera-Camotán, located to the North of the zone in the andesites that constitute the local base, represents the extreme of the mixed group, with the maximum percentages of Mg and Ca. To this group correspond the low enthalpy springs and shallow circulation. The concentration of chlorides in the springs of the first group varies from 55 to 200 mg / l, and boron varies from 1.2 to 7.4 mg / l, which suggests that these waters are of deep origin. Their high concentrations of sulphates are due to the oxidation of the H_2S of geothermal origin when interacting with dissolved oxygen in the water of meteoric origin at shallow depths. The concentration of lithium in sulphated waters varies between 0.6 and 2.0 mg / l, while in some bicarbonates is less than 0.11 mg / l. This difference is also indicative of a deep origin for sulphated waters, which is also confirmed by the Cl / B ratio of these same waters

2.3.2 Chemical Characteristics of Gases

According to its chemical composition, the gases of La Soledad correspond to those expected in a geothermal environment, since CO_2 is the most abundant and H_2S was detected in significant quantities (between 1.41 and 4.10 per thousand molar, excluding the fraction of steam). The formation of NH_3 and CH_4 is favored at low temperatures, while that of CO_2, N_2 and H_2 is favored at high temperatures. The concentration of NH_3 and CH_4 in the La Soledad gas samples is low, which implies the existence of high temperatures. However, H_2 could not be detected as expected. The nitrogen-helium-argon ratio indicates that hydrotherapy may be due to the fact that fluids have circulated deep in the earth's crust. The N_2 / Ar ratio is very similar to that of air, while the He is found in concentrations higher than atmospheric, probably due to the contribution of helium by radioactive decay.

2.3.3 Geothermometry of Water and Gases

To estimate the temperature of the subsoil, geothermometers of liquid phase and gas phase were applied. The liquid phase temperatures were obtained between 181 °C (Huaxtla springs) and 207 °C (La Soledad springs) according to the Potassium-Sodium geothermometer, and between 51 °C (La Calera) and 196 °C (La Soledad) according to the sodium-potassium-calcium geothermometer. The gas geothermometer of D'Amore-Panichi calculates relatively low temperatures that vary from 119 to 141 °C. This could be due to the fractionation that the gases experience through their route, from the deposit where they originate to the discharge zone.

2.4 Geophysics

2.4.1 Geoelectric Prospecting

From November 1985 to May 1986, 75 vertical electric boreholes were carried out under the Schlumberger arrangement in the La Soledad area, with semielectrodic separations of 500 to 4000 meters. The survey lines covered virtually all surface manifestations. From the analysis made to the data, isorresistivities planes were generated for each of the separations, considering values of 15 Ωm or less as minimum resistive. By combining the minima thus obtained, an anomalous zone of irregular shape and large extension (approximately 15 km^2) was obtained in the area of La Soledad, limited by the El Mirador ranch to the South, the La Soledad ranchería to the East, Cerro Las Palomas to the North and the El Chicharrón and Jacal de Piedra domes to the West. Additional other anomalous areas of smaller dimensions, three of which appear concentrated to the North of La Soledad, also appear in the surroundings of the ranches of Huaxtla, Pedazo Grande, San Lorenzo and Huilotán. The anomalous area of 15 km^2 is remarkably wide, when compared to the minimum resistivity normally found when carrying out geoelectric studies in geothermal areas, which rarely exceed 5 km^2 of surface area. It was also calculated that the thickness of the conductive horizon would be approximately 1.5 km, which implies a volume of interest, probably associated with a deposit in the subsoil, of 22.5 km^3. Within the mentioned anomalous area, three zones of greater geothermal interest were located, based on the smallest values of resistivity. These three zones total approximately 5.53 km^2, and represent the area most likely to be associated with a geothermal deposit in the subsoil (Palma-Pérez, 1986).

2.4.2 Gravimetry and Magnetometry

Gravimetry studies were carried out in the area in 1987, with the aim of defining the structural aspects of the area. For this, 740 stations were observed spaced every 500 meters, in such a way that an approximate area of 450 km^2 was covered. According to the results obtained, it was interpreted that the basal andesitic unit is tilted to the Southwest with normal NW-SE direction faults and associated with the Rio Grande de Santiago, Mesa de San Juan and the El Chicharrón dome. In addition, two tabular bodies of probably diabasic composition were interpreted, apparently intruding on the andesites, one associated with the Cerro Piedras de Amolar and the other on the right margin of the Río Grande de Santiago, in front of La Soledad. The magnetometric study, on the other hand, was carried out simultaneously with the gravimetric, covering the same area and observing the same number of stations. The objective of this study was to investigate the presence of faults and fractures, and their probable relationship with thermal manifestations, defining in a general way the dominant structural patterns. The interpretation of the results was consistent with the geological studies and with the gravimetric interpretation, confirming that the andesites are tilted to the Southwest with normal NW-SE direction faults. It was also confirmed that the zone is affected by regional faulting systems NE-SW, in addition to NW-SE faults, although it was not possible to detect the E-W management structures, due to their limited development and their small size (Ballina-López, 1987).

3. SPONTANEOUS POTENTIAL (SP)

The SP is an electrical prospecting method. The method consists of measuring the difference of the surface potential between two points, where the common denominator of the SP generation is the flow of groundwater by a porous medium. Its use has been extended to solve problems of environmental impact, filtration of groundwater, and in the field of civil engineering. Since 1970 the SP has been taken up for the study of geothermal fields and the study of volcanoes, mainly looking for relationships between geological structures and active hydrothermal systems (Corwin and Hoover, (1979), Reynolds (2011)). The proposed mechanisms to explain SP anomalies are based on electrokinetic and thermoelectric effects. The electrokinetic effect associated with the downward flow of water, in purely hydrogeological environments, will produce an SP anomaly with negative surface values, however if this hydrogeological system is altered by an increase in temperature by a magma chamber or an intrusive body, a water vapor-liquid water interface will be observed and the anomaly will be positive (thermoelectric effect) (Sasai et al. (1997); Di Maio et al. (1998); Aubert et al. (2000); Finizola et al. (2002), Finizola et al. (2004)). The application of the SP in the geothermal area of La Soledad had the purpose of delimiting the hydrothermal system and identifying the active fault systems that serve as conduits for thermal fluids, in areas of high sub-surface heat flux. Geological structures, hydrothermal systems and high permeability zones are related to the infiltration of water into the geothermal area.

3.1 Field Work

The acquisition of the data was made a total of 2,020 measurements of SP every 20 m, which correspond to approximately 40.4 linear km of laying (Figure 4). The SP measurements were made by forming loops (closed profiles or profiles connected at both ends to other profiles) in order to evaluate and correct the drift generated during the acquisition of the data. As can be seen in Figure 4, the spatial distribution of the profiles made in this area only covers the areas near the Rio Grande de Santiago, which is the deepest part and presents the area with the greatest thermal manifestation. On the other hand, the zone NW and SW, could not work due to access problems of the owners.

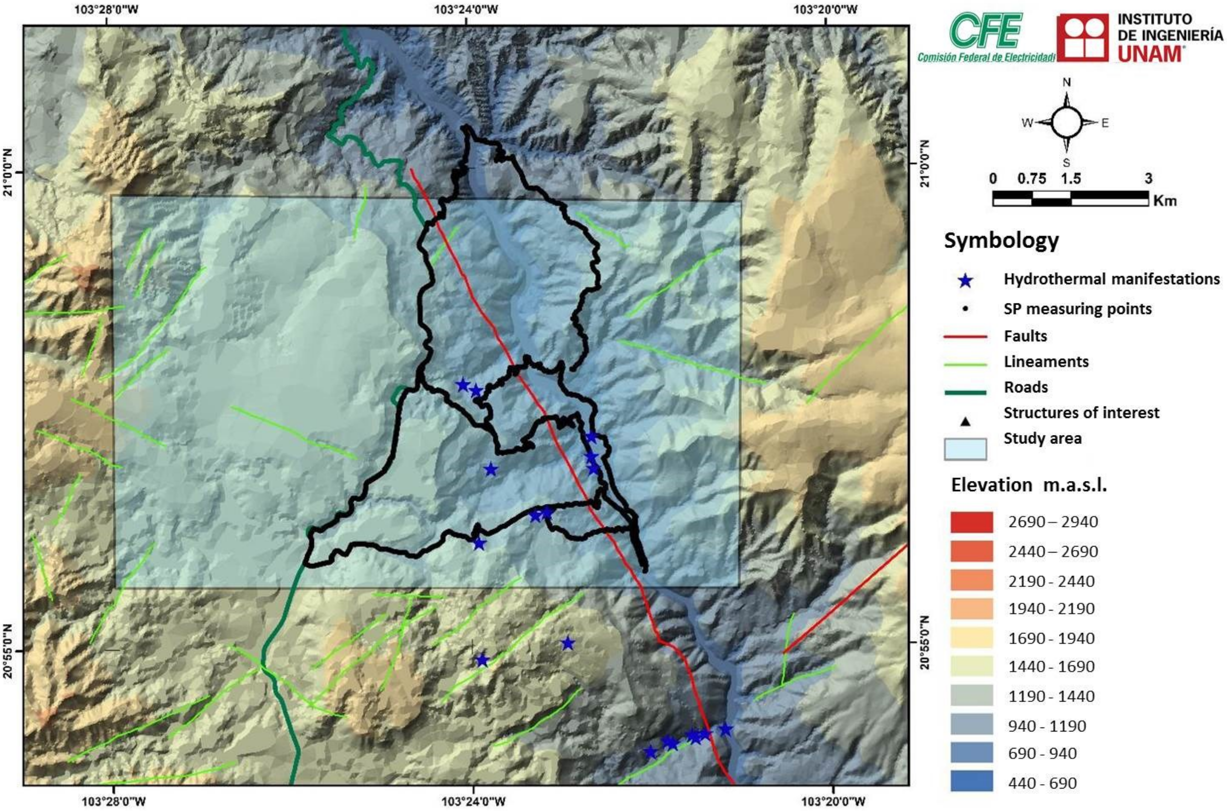

Figure 4: The SP measurement points made within the geothermal area of La Soledad are shown in black color.

3.2 Acquisition of SP Data

The acquisition was made in an approximate time of two months, in which GPS points were also recorded in each existing thermal event, in this case fumaroles. The equipment used consists of 1) a pair of impolarizable electrodes (PVC tubes filled with Cu / $CuSO_4$ copper sulphate solution and a micro-porous end made of wood), 2) a high impedance multimeter, 3) a 300 meter copper cable, 4) a GPS, 5) a picoleta, 6) a field notebook and 7) a couple of plugs (Figure 5).

Figure 5: Equipment used in the acquisition of SP data.

The Barde-Cabusson & Finizola technique (Barde-Cabusson & Finizola, 2013) was used for field measurements and data processing. The first reference electrode (Base) is placed and a small hole is made (approximately 10 cm deep) at 20 m from the reference electrode and the other electrode (mobile) is placed. Later it is connected to the cable and the resistance and SP are measured. Measurements are made every 20 m until reaching the end of the cable, then the base electrode is disconnected to continue with the next station. The measurements are made by forming a loop (closed profile in order to evaluate and correct the drift suffered during the acquisition of the data). After the data collection in the field, the entire database is reconstructed from a single station.

3.3 Data Processing

Data processing is based on the following corrections:

Correction by reference: It is done to join the different parts of the same SP profile, correcting several changes of position of the reference electrode. Each section of the profile must be referenced with the last point of the previous section. The profiles will be moved section by section in the direction in which the measurements were acquired.

Closure or loop correction: It is the correction due to drift, since it increases from the first point to the last one for the acquisition time period. This drift must be corrected since the first and the last point must be theoretically equal, this does not happen in practice due to environmental perturbations. This correction is made with respect to a selected fixed profile. This must contain more than 100 measurements made in the same day and be located in the area of interest.

Correction by source or geohydrologic feature: It is the correction from a geohydrological source (river, lake, water well, sea, etc). A measurement point is taken at that source and theoretically the value must be 0 mV, so this value must be subtracted or added to all the profiles to comply with the above (Figure 6).

With these first three corrections, the first map of SP is obtained (Figure 6), obtaining the following results:

- A positive anomaly of SP (+ 185 mV) is observed that is in the Southeast. These values are attributed to high permeability zones, water accumulation zones and hydrothermal systems, which are transported through fault systems connected to the heat source. These values obtained, although they surpass 200MV, are interpreted as a permeable zone, in which there is possibly a part of the hydrothermal system which could have a greater extension towards the South part of it.
- A point is observed in the East part of approximately 40 mV, which is surrounded by high values (160 mV). This point is considered an area of water infiltration. at that point there is both infiltration (negative charges) and a permeable area associated with a hydrothermal system (positive charges).

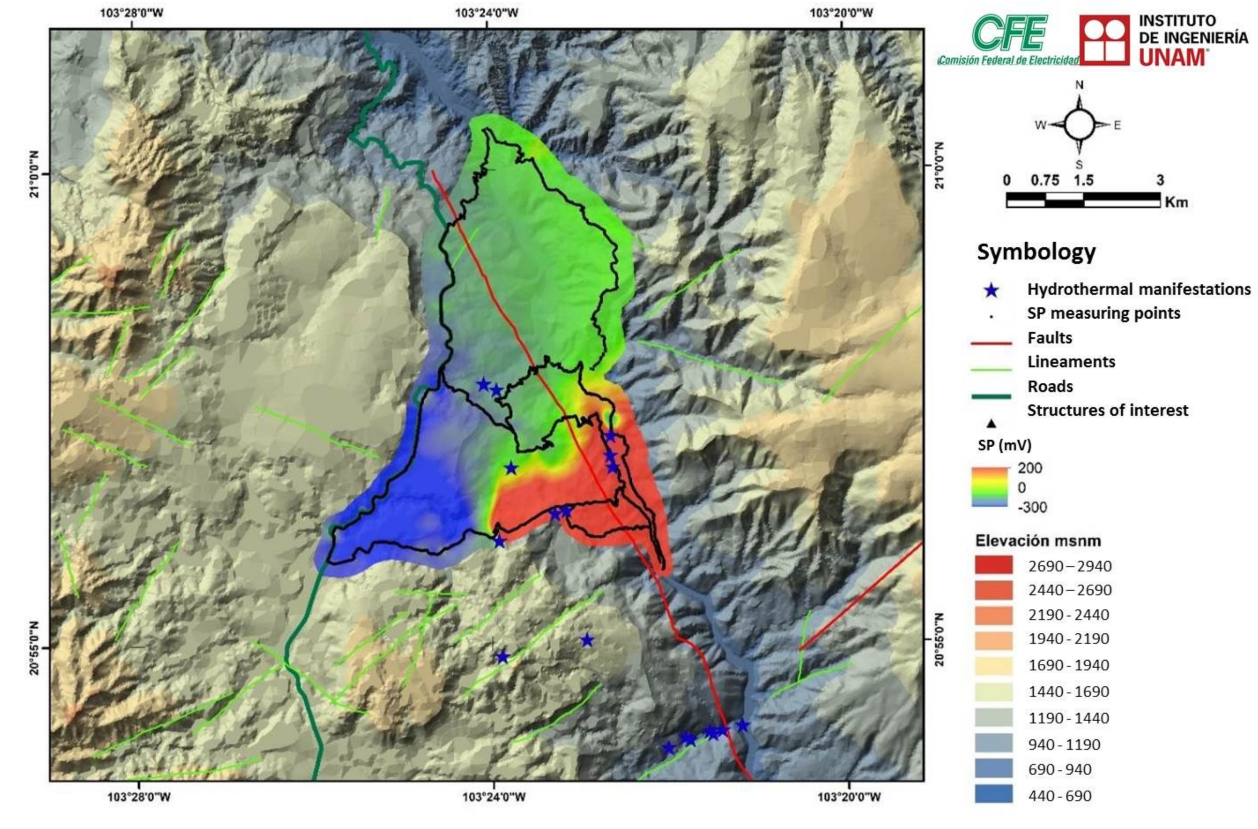

Figure 6: Map showing the SP model with geohydrological correction and plant measurement points.

Topographical correction: It is the correction due to the effects of altitude in the terrain. The topography affects the potential since it tends to negative values in the areas with higher altitude (Mlynarski, 2001). To perform this correction, the altitude of each measurement point is required, and it is considered the highest elevation part of the area of interest, using several profiles, in order to obtain the SP *vs* Elevation (altitude) ratio. This ratio allows for obtaining the coefficient mV / m with which a linear regression is performed.

In general, groundwater flows downward along the sub-horizontal layers, resulting in outcrops at the interface of permeable and watertight lava flows (thick lava flow beneath a slag bed, for example). When a geological barrier, such as a boiler wall, prevents downward flow, an aquifer is formed inside it. Such a scheme explains the so-called "topographic effect" where the potential increases when the altitude of the topography decreases. Very often, the authors express the negative ratio of $\nabla\varphi / \nabla h$ (in mV / m) or $\nabla\varphi / \nabla P$ (in mV / MPa) as the coefficient of electrokinetic effect. The range of this coefficient is between -1 and -10 mV / m, with an average value of around -2 mV / m. In this case, the negative expression of the topographic effect is represented in the coefficient $\nabla\varphi / \nabla h$ (in mV / m), due to the steep topography a coefficient was obtained, the obtained value is: -0.49mV / m, this due not only to the topography that is in the area, but also to the way in which the data were obtained, since due to this the profiles made are not parallel or radial, which makes it difficult to obtain this coefficient. For this reason there is greater reliability to the interpretation without such correction (Figure 7).

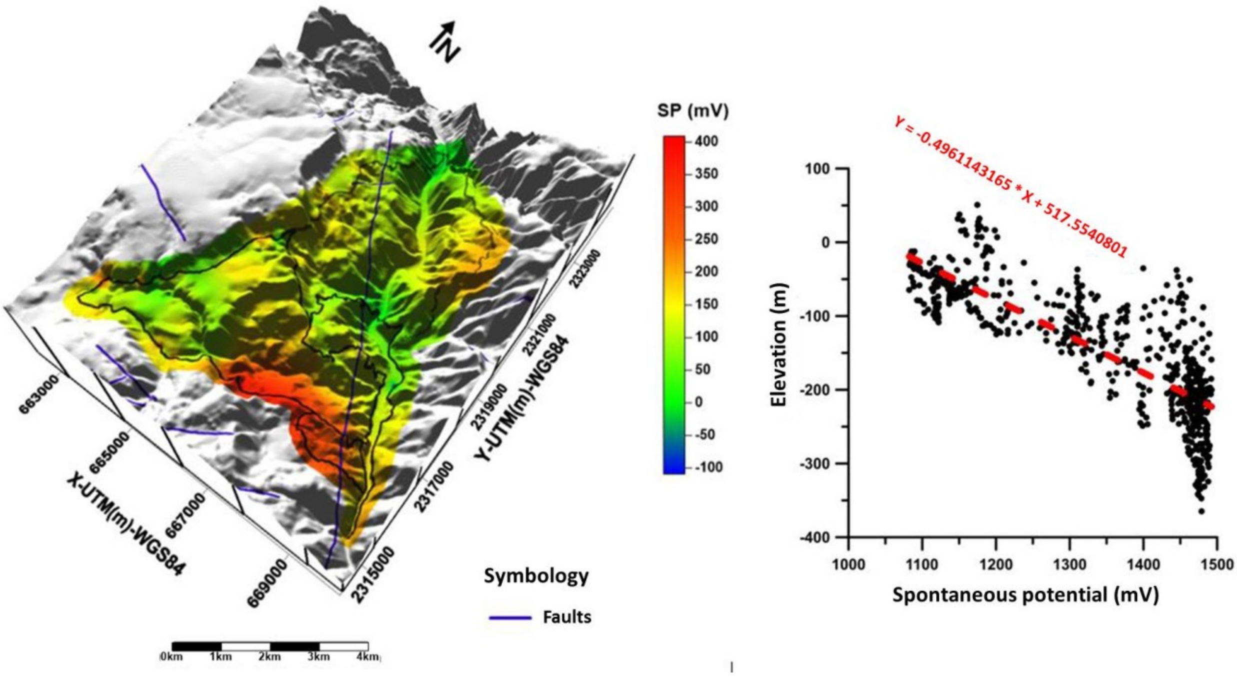

Figure 7: Left-Map of SP with topographic correction. Right-Graph that shows the value of the mV / m coefficient.

3.3 SP Results

A better interpretation of the map obtained without the topographic correction can be observed, because although the same tendency is observed that the positive values are to the South of the area of interest, the values of SP in the whole map rise considerably from 200 mV to 400 mV (Figure 7). This is because the coefficient obtained was only made with the majority of data from a single profile. A single profile was used because the abrupt topography limited measuring from radial or parallel ways, causing a great variety of slopes to obtain the coefficient $\nabla\varphi / \nabla h$. For this reason we can see a better interpretation in the SP map, considering up to the geohydrological correction. Figure 8 shows the final result of the SP map, the hydrothermal manifestations found within the area and the faults obtained from the Mexican Geological Survey (SGM by its name in Spanish Servicio Geológico Mexicano) and the INEGI.

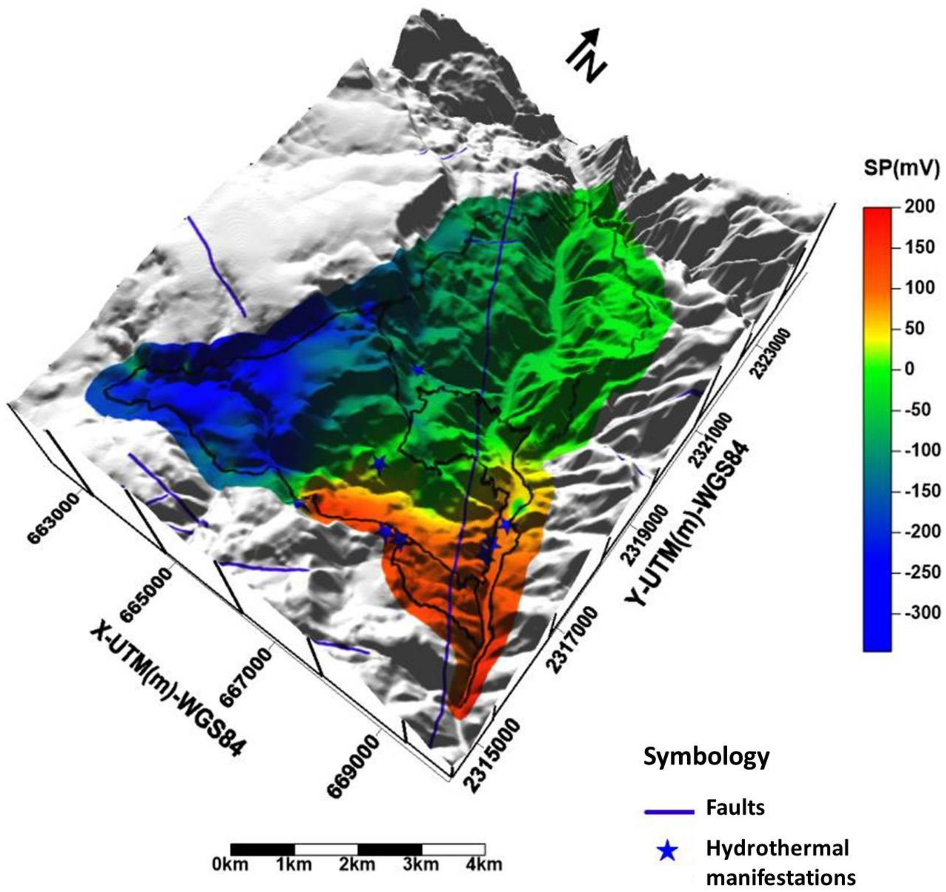

Figure 8: Final model of the SP map, local faults and hydrothermal manifestations in the geothermal area.

4. SEISMICITY

Volcanic, tectonic and seismic activity occurs together. This results in the association that is frequently observed in geothermal areas (located in areas with volcanic and tectonic activity) and seismicity (Foulger, 1982). Therefore, the analysis of seismicity in a geothermal area is important due to the close spatial relationship between earthquakes and geothermal activity (Ward, 1972). Pall (1991) indicates that to create and maintain a geothermal system, three factors are necessary: high permeability, a source of heat and circulation of hydrothermal fluids. The analysis of seismic activity provides important information about the three factors. Because earthquakes occur over faults, seismically active fault systems (associated with high permeability) can be located by accurately locating earthquakes (Ward, 1972). On the other hand, because the S wave is strongly attenuated when it passes through partially molten rock or hydrothermal fluids, the seismicity can define the location of the heat source (associated with a magma chamber, an intrusive body or a gradient) or areas with high content of hydrothermal fluids. He notes that seismicity does not behave in the same way in all geothermal areas. Some geothermal areas are characterized by an increase in the number of earthquakes; others show seismic activity similar to the surrounding regions, and some geothermal areas do not even show seismic activity (Pall, 1991).

As part of this work, a seismic network was installed in the La Soledad area. 17 seismic stations were placed to locate the local earthquakes or micro-earthquakes and define the fault systems within the study area directly associated with the geothermal activity. Three stations PR02, TS01 and SE01 were used at the regional level (Figure 9). The monitoring of the seismic activity lasted approximately four months. The time is sufficient for the registration of seismicity, both regional and local, so valuable information was obtained to define the active fault systems. The seismic stations registered three types of seismicity: local, regional and distant earthquakes. For the purpose of this article, only local seismicity was considered.

To obtain a good location of the earthquakes it is necessary to have a suitable P-wave velocity model. The velocity model for the La Soledad area was obtained from the tomography with seismic noise. With the tomography it was possible to estimate the distribution of the S and P wave velocity in three dimensions. The location program uses a model in which the speed variation is only in the z direction (1D model). Then an average of the P wave velocity obtained for the whole area was obtained in order to have the 1D model. The result is shown in Table 1.

Table 1: P wave velocity model to locate the local earthquakes, obtained from the seismic noise tomography.

Depth of the layer [m]	P wave velocity [m/s]
0	3650
400	4020
1070	4450
1610	5150
4000	5500

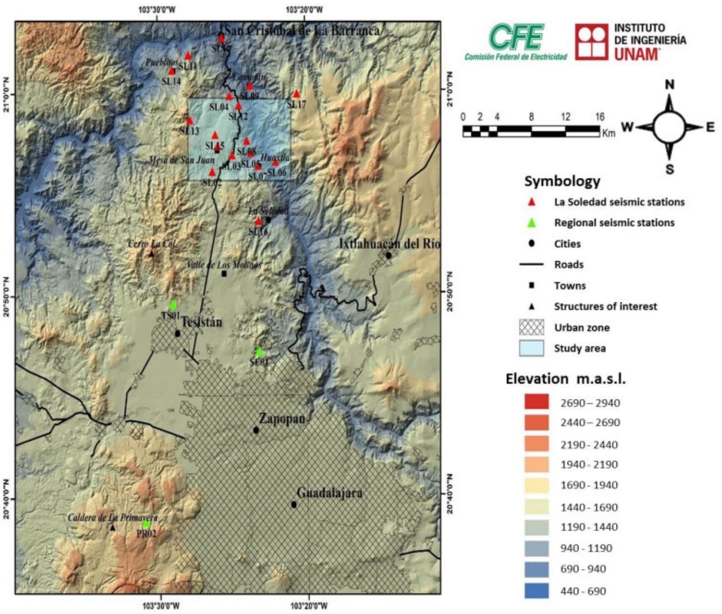

Figure 9: Distribution of local and regional seismic stations in the geothermal area of La Soledad and its surroundings.

Because the earthquakes considered local are relatively small in magnitude, the amount of energy released is well represented by the magnitude of coda proposed by Havskov (1983) in equation (1):

$$Mc=1.59+2.4*log10\ (T)+0.0004*(D) \quad (1)$$

where *Mc* is the magnitude of coda, *T* is the duration of the coda in seconds and *D* is the epicentral distance in kilometers. The above equation has been used to estimate the magnitude of the earthquakes that are located within the Mexican Volcanic Belt. Therefore, it was used to calculate the *Mc* of the local earthquakes of the geothermal zone of La Soledad.

To estimate the Vp / Vs ratio, the modified Wadati diagram was used, which identifies the farthest station that recorded a particular event. That is the one with the largest P and S wave arrivals ($t_{p,\ max}$ and $t_{s,\ max}$). The following operation is performed to obtain the values T_p and T_s by means of equations (2) and (3)

$$T_p=t_{p,}-t_{p,station} \quad (2)$$

$$T_s=t_{s,}-t_{s,station} \quad (3)$$

where t_p, station and t_s, station are the values of the stations that recorded the event. The values of T_p and T_s are plotted and a linear regression is performed to obtain the best fit. The value of the slope of the subtraction is the estimated value of Vp / Vs (Figure 10).

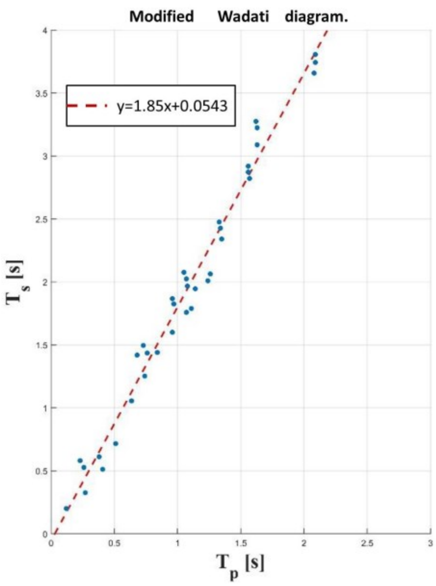

Figure 10: Estimation of relation between Vp / Vs.

The estimated value for the ratio of Vp / Vs obtained by the modified Wadati Diagram is 1.85.

4.1 Locations of Earthquakes

During the study period, five local events were recorded in the geothermal area of La Soledad. The events occurred in a period of 8 days, during the months of February and March of 2018. The waveform of the five events shows great similarity for the stations that recorded the earthquakes, probably because the mechanism of rupture is the same. In Figure 11 you can see the signal of stations SL08 and SL17 for the five earthquakes. It is observed that the waveforms are quite similar, both in the arrival of the P wave and in the arrival of the S wave, as well as in the whole signal in general. The five events were located in the same area within La Soledad area, due to the great similarity in the waveform and, therefore, in the P and S wave arrivals.

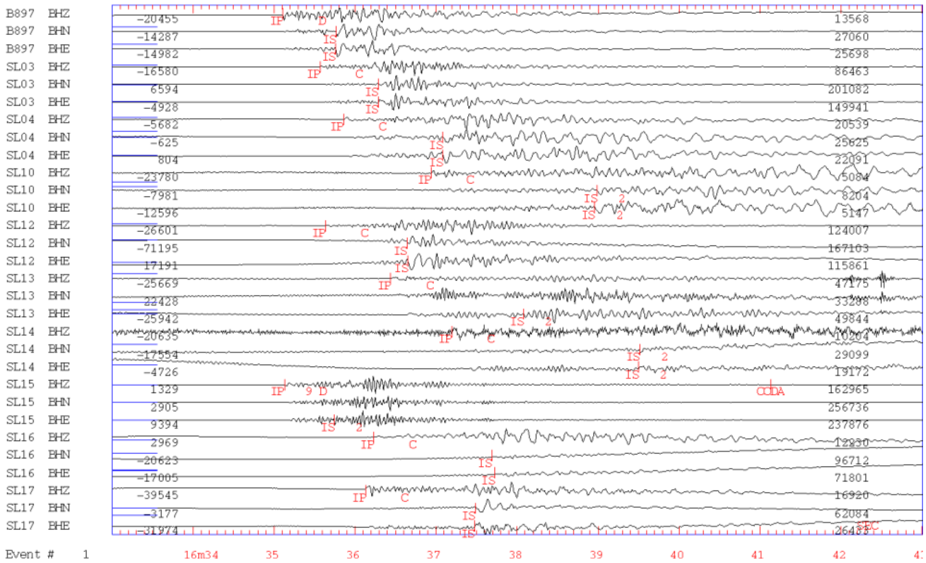

Figure 11: Waveform of the event of March 1, 2018 at 7:16:34 UTC. The time window is 10 s and a bandpass filter from 1 to 30 Hz was used for a better visualization of the signals. Note: Station B897 is SL08 and SL15 is SL05.

The earthquakes are located approximately 1 km Northeast of the town of San Lorenzo and 1 km East of Huilotán (Figure 12). They cover an area smaller than 1 km^2. The errors in latitude and longitude are low, in the order of 500 meters. The error in depth is greater, on the order of 1000 meters. The depth of the earthquakes is on average 3275 m and the average Coda magnitude is 0.7.

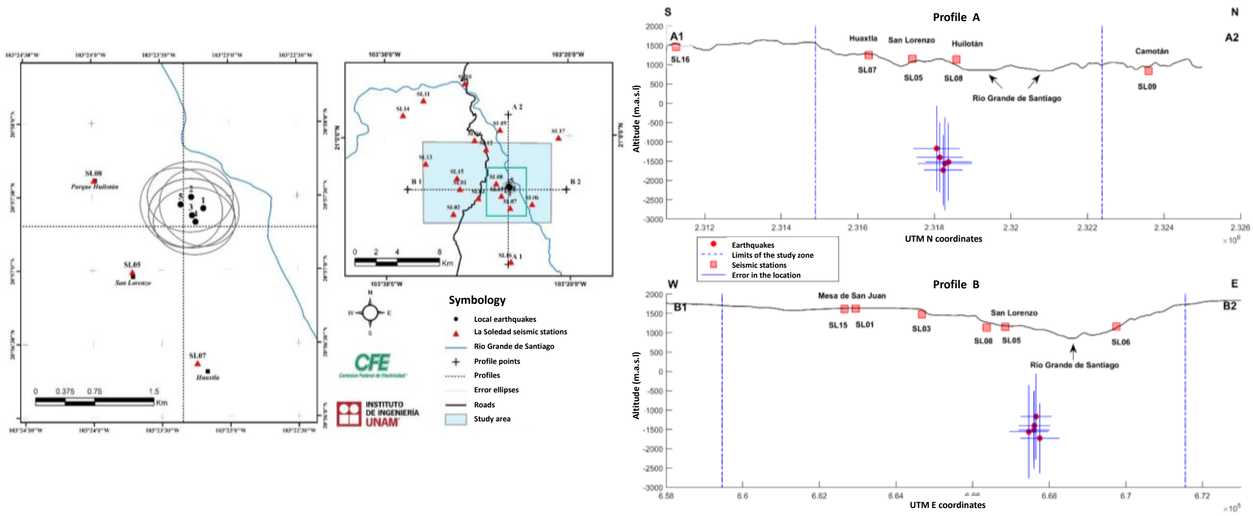

Figure 12: Location of seismic local events in the geothermal area. Top) Map of the location of local earthquakes. The events are located in a region bounded by the Rio Grande de Santiago and stations SL08 and SL05. Below) S-N and W-E profiles of seismic events. The earthquakes are at an altitude of -1000 to -2000 m.a.s.l, below the towns of San Lorenzo and Huilotán. The error in depth is greater than the errors in latitude and longitude.

Table 2: Location information for the five events.

Events	Year	Month	Day	UTC hour	Latitude	Longitude	Depth [Km]	Latitude error [km]	Longitude error [km]	Depth error [km]	Mc
1	2018	2	22	04:50:42.7	20.95696	-103.38651	3.530	0.5	0.5	0.9	0.4
2	2018	2	27	23:27:21.2	20.95824	-103.38797	3.317	0.6	0.4	1.0	1.0
3	2018	3	1	07:16:34.7	20.95617	-103.38789	3.201	0.6	0.4	0.9	1.0
4	2018	3	1	07:24:03.2	20.95543	-103.38748	2.965	0.6	0.4	1.1	0.9
5	2018	3	1	07:57:40.1	20.95741	-103.38927	3.362	0.7	0.5	1.2	0.4

4.2 Focal Mechanism

The focal mechanism is the most important parameter once the location and magnitude of an earthquake is determined. It is used to determine the geometry of the faults as well as to infer the style of failure and the stress regimes of a particular region (Havskov J ., Ottemöller, L., 2010).

In order to obtain focal mechanisms of local seismicity, the polarities of the P-wave arrivals (dilatational and compressional) were taken into account and calculated through the FOCMEC program (Ottemöller et al., 2016). The focal mechanism can be defined because, in most of the stations that recorded the events, the polarity of the arrival of the P wave is well defined. For example, the focal mechanism (Figure 13) of the event of March 1, 2018 at 7:16:34 UTC hour was obtained, in which the 10 P-wave polarities of the 10 stations that recorded the event are distinguished. The mechanism defines a normal fault with a left lateral sliding component. The parameters of the focal mechanism are: strike = 321 °, dip = 53 and slip = -64 ° (Figure 13).

Due to the close spatial and temporal distribution of the registered local events, and to the similarity in the waveform, it is possible to perform a composite focal mechanism by gathering the polarities of the five events. The fault plane solution and the parameters are exactly the same as those obtained for the event on March 1, 2018 at 07:16:34 UTC time. The composite focal mechanism is shown in Figure 14.

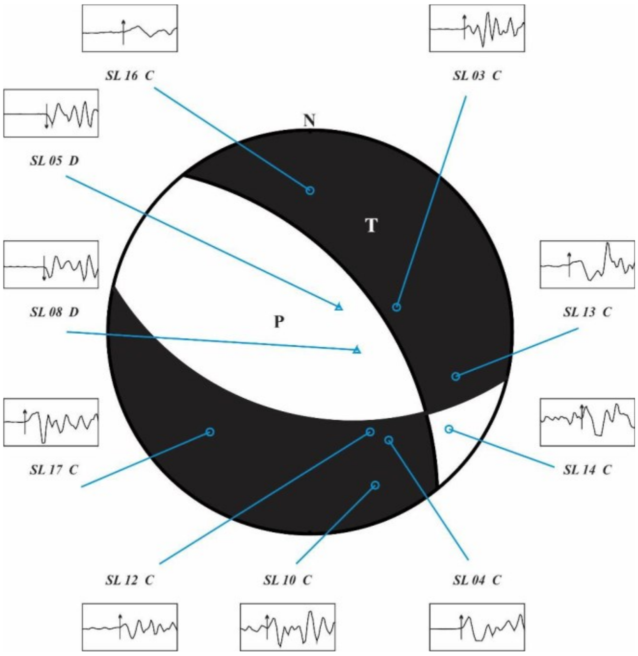

Figure 13: Focal mechanism of the event of March 1, 2018 at 07:16:34 UTC time obtained by means of the P wave polarities. The circles indicate compressions and the triangles dilatations of the P wave arrival, as shown in the waveform of the rectangles. The polarity of the station SL14 is the only error in the solution of the focal mechanism, probably because the polarity or the error in depth is not clearly observed.

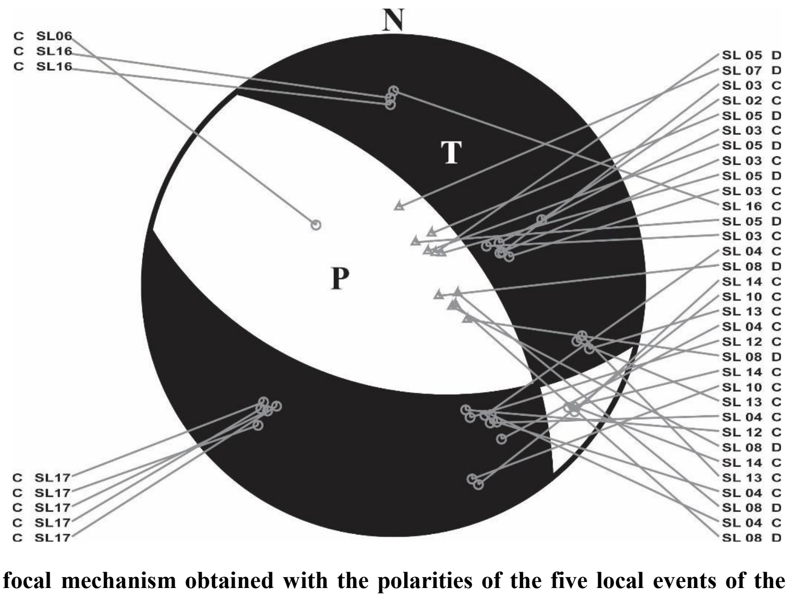

Figure 14: Compound focal mechanism obtained with the polarities of the five local events of the geothermal zone of La Soledad. The circles represent compressions while the triangles indicate dilations

4.3 Seismicity Results

With the network of temporary seismic stations that were installed for approximately four months, only five localized earthquakes occurred in a period of 8 days, between the months of February and March 2018. The earthquakes were located approximately 1 km Northeast of San Lorenzo and 1 km East of Huilotán, grouped in an area less than 1 km^2, and are located at a depth of between 3 and 3.5 km. The five recorded events occurred days after the February 16, 2018 earthquake of magnitude Mw 7.2 and were probably induced by this great earthquake. The fault system that generated the events has a NW-SE address and is possibly the most active system in the area.

5. POISSON COEFFICIENT

Profiles and sections were obtained for the Poisson Coefficient (υ) by means of equation (4):

$$\upsilon = \frac{1}{2}\frac{(\frac{v_p}{v_s})^2 - 2}{(\frac{v_p}{v_s})^2 - 1} \quad (4)$$

The Poisson's coefficient is defined as the deformation perpendicular to the direction of a force acting on a body. The experimental and theoretical results indicate that the fracturing of a rock, due to some fluid, will cause an increase in the Poisson Coefficient (Silitonga et al. (2005)), see Figure 15.

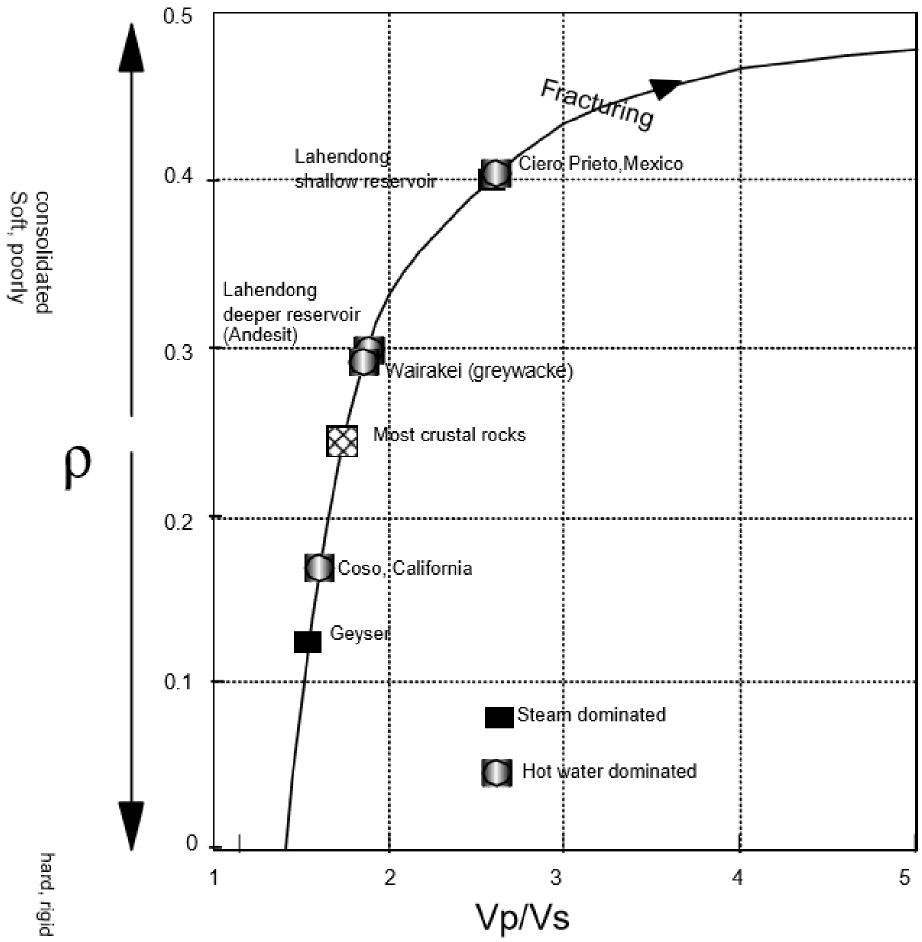

Figure 15: Vp / Vs ratio versus Poisson's coefficient for some geothermal fields.

The depth sections were carried out for Vs, Vp and Poisson's Coefficient, with profiles A-A ', B-B' with sections at a depth of -1300 m.a.s.l, with respect to S-wave velocity and Poisson's coefficient. The designation of the location of the profiles was considering the crossing of the anomaly delimited by the SP and the local seismicity (Figure 16).

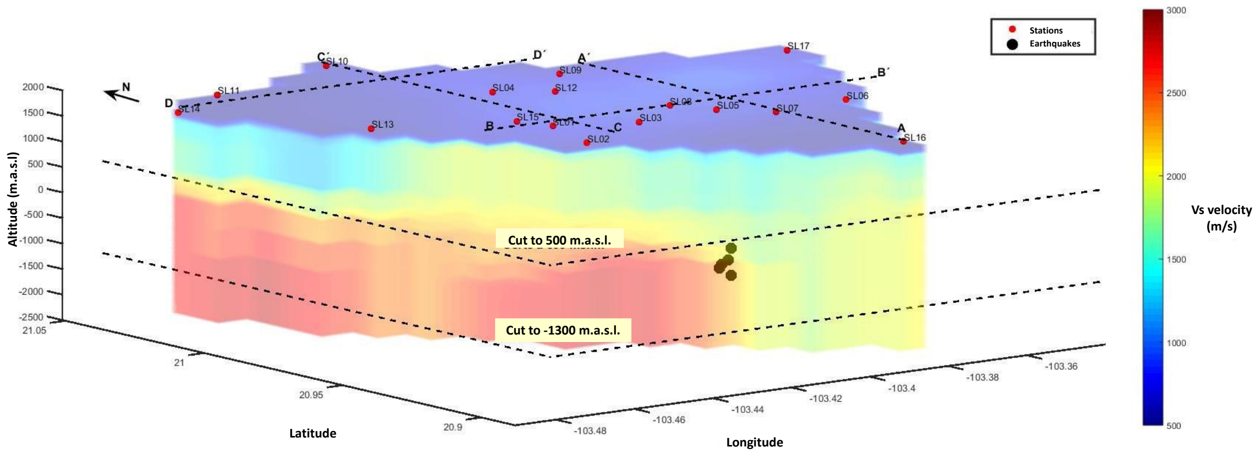

Figure 16: Location of profiles A-A 'and B-B'. Profile C-C 'is omitted for this analysis.

In profile A-A' (Figure 17) of S-wave velocity, there is a lateral velocity contrast. To the South, the velocity is about 2000 m/s (low velocity zone), while towards the North the velocity is 2500 m/s, on average (high velocity zone). The local seismicity is located right at the border between the low and high velocity S-wave regions. This border is possibly a normal fault with dip to the South, therefore, the solution of the focal plane failure plane obtained by means of the local seismicity (Figure 12) would be in the WNW-ESE direction. This result is consistent with the fault systems found in the geothermal area of La Soledad (Structural Geology), where it is mentioned that the WNW-ESE system is the most recent. The Poisson Coefficient in profile A-A '(Figure 17) defines an anomalous zone towards the South, starting from the town of Huaxtla, with an average value of 0.36. This value corresponds to a geothermal zone dominated by hot water and fracturing of the rock (Figure 19).

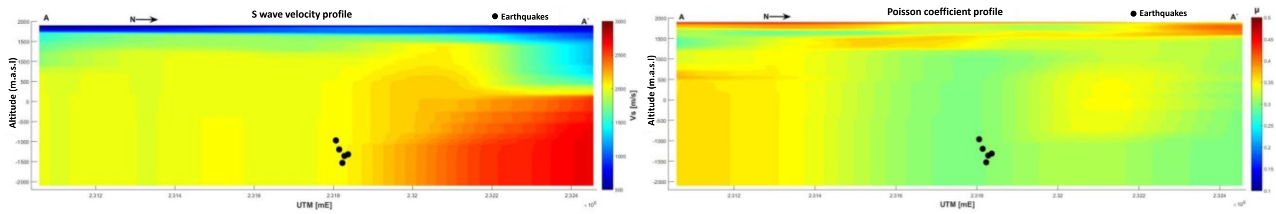

Figure 17: Profile A-A 'of S-wave velocity and Poisson's coefficient passing through the registered local seismicity.

Profile B-B '(Figure 18) of S-wave velocity also defines a contrast between a high-velocity zone and a low-velocity zone. The first with average S wave velocity of 2500 m / s and the second with a velocity of 2000 m/s, on average. The seismicity is located in the boundary between the low and high velocity regions. The Poisson Coefficient in this profile defines two zones of high values. The first one, towards the East, with an average value of 0.35, is related to the area of interest delimited by the SP. The second one, towards the West, with an average value of 0.4 that is associated with a high density body in this place.

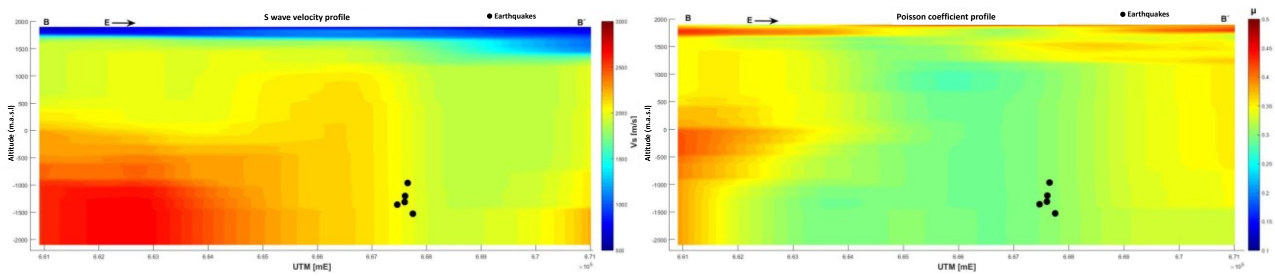

Figure 18: Profile B-B 'of S-wave velocity and Poisson's coefficient passing through the registered local seismicity.

Finally, the S-wave velocity cut performed at -1300 m.a.s.l (Figure 19) defines a low velocity zone (2000 m/s on average) to the Southeast of the exploration area. There is an area of 2300 m/s on average that extends from Southeast to Northwest, and that occupies the center zone. Finally, there are three high velocity zones (2500 m/s on average) that occupy the Northeast, Northwest and Southwest part of the exploration area. The Poisson Coefficient (Figure 23) in the Southeast zone (low velocity anomaly of S wave) is 0.35, which agrees with the values obtained from profiles A-A 'and B-B', and with the area delimited by SP method and local seismicity. There are high values of Poisson Coefficient in the West zone, but they are related to a high density body.

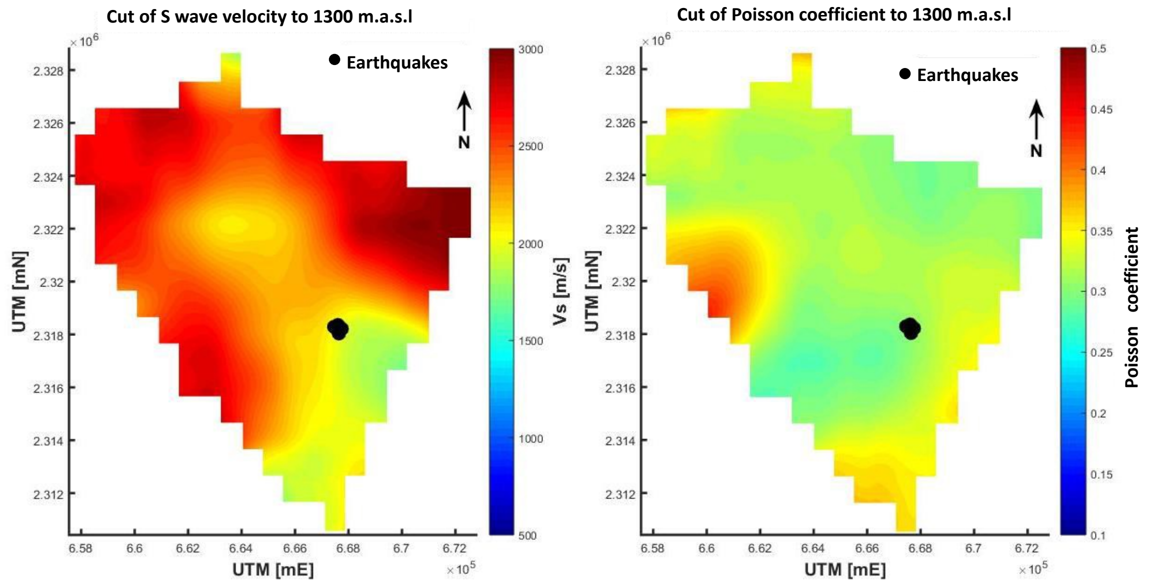

Figure 19: Cut at an altitude of -1300 m.a.s.l for the S wave velocity (left) and the Poisson Coefficient (right).

6. RESULTS OBTAINED IN THE AREA OF LA SOLEDAD

The results of the measurement of SP, the analysis of local seismicity and the Poisson Coefficient in the geothermal area of La Soledad allow us to make a geophysical model of the area and correlate it with the available geological, geochemical and geophysical information. The highest SP values of up to 185 mV are located towards the Southeast of the study area, around the towns of Huaxtla and San Lorenzo (Figure 20). Generally, these SP values are related to areas of high permeability, water accumulation and hydrothermal systems. In this place there are sulphated water springs, which are considered to be of deep origin due to the content of chlorides and boron (Geochemistry). There are also three anomalies of low resistivity between the towns of Huaxtla, Pedazo Grande, San Lorenzo and Huilotán (Geophysics). Therefore, the SP delimits an area of geothermal interest that correlates with the Geochemical and Geophysical information. The seismicity is located East of San Lorenzo and Huilotán, at a depth of between 3 and 3.5 km. Defines a fault plane in the NW-SE direction and limits the SP anomaly to the North (Figure 24). It is probable that this fault system is the conductor of the geothermal fluids of the area that are the cause of the hydrothermal manifestations and the anomalies of low resistivity.

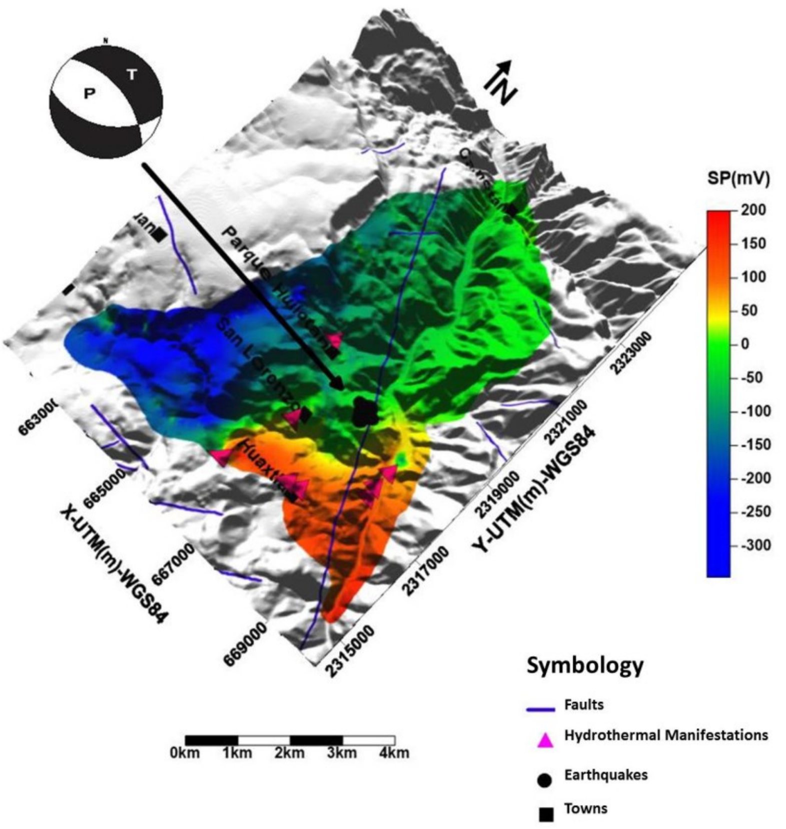

Figure 20: Spontaneous potential in the geothermal zone of La Soledad, together with the local seismicity and the hydrothermal manifestations of the area.

The boundary of the SP anomaly indicates the boundary of the probable hydrothermal system of the exploration area, located between the towns of Huaxtla and San Lorenzo, with a NE-SW trend. To the Northeast, the inferred normal fault acts as a barrier to this probable system (Figure 21). The limit of the S-wave low velocity anomaly of 2000 m/s coincides with the limit defined by the SP, which confirms an area with probable geothermal potential if it is considered that in the same place there are two anomalies of electrical resistivity and the Springs of Huaxtla and Pedazo Grande (Figure 21). Within the S wave velocity anomaly there are two other zones with values lower than 1800 m/s; the first one surrounds the two electrical resistivity anomalies located to the Southeast of the study area, and the second extends to the South outside the exploration area of the present article (Figure 21). Finally, the anomaly limit of the Poisson Coefficient is seen in Figure 25. It extends mainly to the Southeast outside of the exploration area and defines an area dominated by hot water and fracturing, delimiting an area of greater geothermal potential that agrees with the area defined by the Department of Exploration (1990) in previous studies (Figure 21).

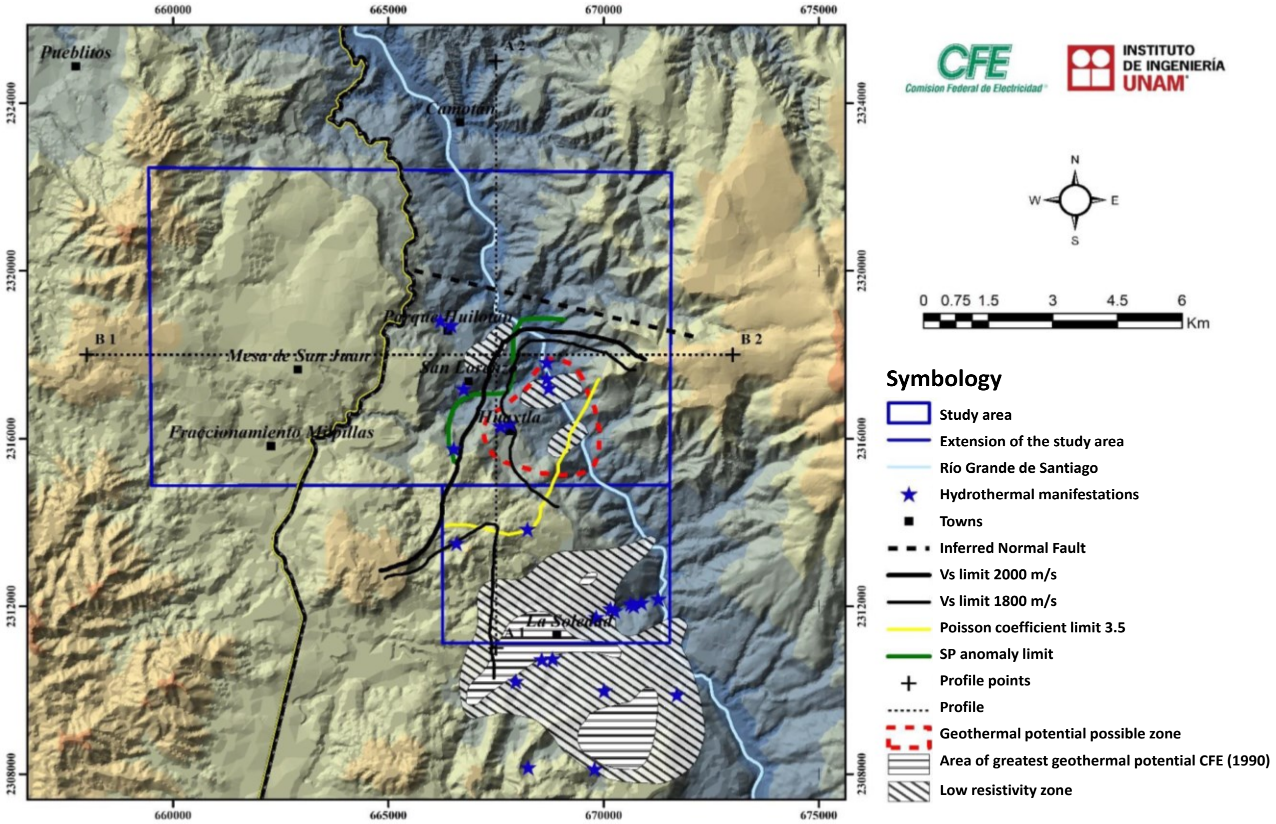

Figure 21: Area with the greatest geothermal potential within the geothermal exploration area of La Soledad.

Based on the SP anomaly, the low-velocity S-wave anomaly, the inferred fault by means of the focal mechanism composed of the local seismicity, the comparison with the electrical resistivity anomalies, and the chemical analysis of the springs made by CFE (1990), an area of potential geothermal potential of approximately 5 km^2 was defined within the area assigned to conduct exploration studies in La Soledad (see Figures 21 and 22). It should be noted that, according to the Poisson Coefficient anomaly, it is very likely that the area of possible geothermal potential will extend to the South, outside the area designated by SENER.

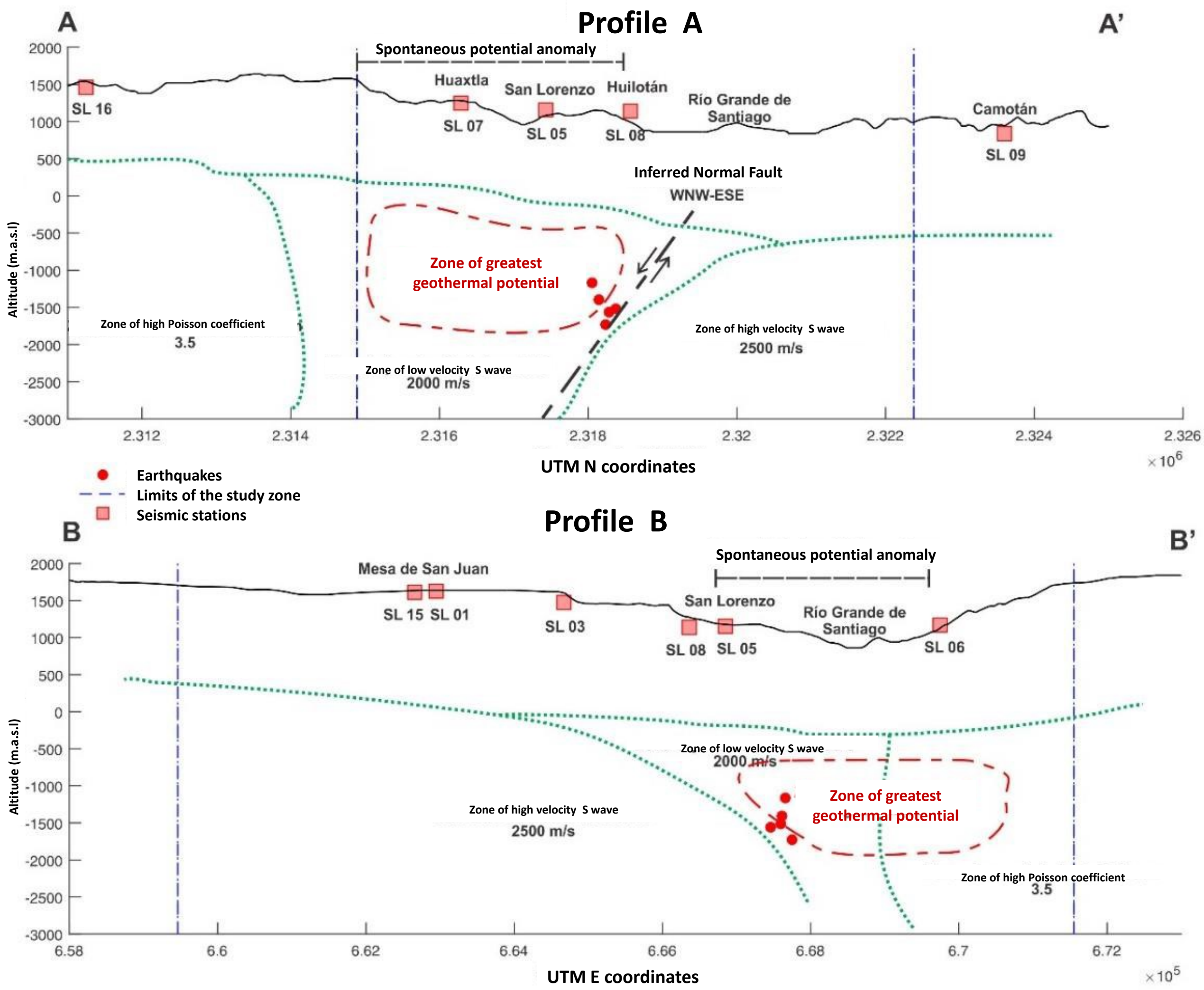

Figure 22: Area with greater geothermal potential, at depth, within the geothermal area of La Soledad. A-A 'profile showing the extension from South to North of the area with the highest geothermal potential. B-B 'profile showing the extension from West to East of the area with the highest geothermal potential.

7. CONCLUSION

The results of the application of SP, together with the registered local seismicity and the Poisson Coefficient, allowed reaching the following conclusions about the geothermal area of La Soledad:

- There is an SP anomaly in the Southeast of the geothermal area of La Soledad of up to 185 mV. This is located between the towns of Huaxtla and San Lorenzo, and has a NE-SW trend. The anomaly is related to areas of high permeability and hydrothermal systems, inferred by the correlation with geochemical information and electrical resistivity.
- The seismic network installed in the geothermal zone of La Soledad registered five earthquakes that were located East of Huilotán and San Lorenzo (approximately 1 km), with depths between 3 and 3.5 km. The seismicity defines a fault plane in the WNW-ESE direction that matches the active fault system of La Soledad. This fault plane limits the SP anomaly to the North and probably conducts the geothermal fluids of the site.
- The Poisson Coefficient anomaly is located Southeast of the geothermal area of La Soledad.
- According to the anomalies of SP, the low velocity of S waves, the local seismicity registered in the area, and the correlation with the geochemical information and the electrical resistivity anomalies, an area of probable geothermal potential of approximately 5 km^2 was delimited to the Southeast of the geothermal area of La Soledad in the vicinity of the town of Huaxtla. It is noted that the zone of possible geothermal potential extends to the South, outside the area defined for this work, due to the anomaly of Poisson's coefficient.
- The geophysical methodologies applied in this article were ideal to define and delimit the extension of the hydrothermal system in the geothermal area of La Soledad, as well as to identify the active fault system of the region through which the hydrothermal fluids that cause the springs are probably rising.

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