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PASSIVE SEISMIC EXPLORATION OF GEOTHERMAL RESOURCES, GENERALITIES

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ABSTRACT

Geophysical prospecting methods: electrical, gravimetry, magnetic, MT, seismic, among others are the disciplines applied in geothermal resources exploration. Particularly, active and passive seismic survey prospection studies allow us to acknowledge the structures that undelay in the underground and the behavior of their interaction with geothermal fluids like magma, gas or water.

According to the way that seismic energy is generated, it changes the way seismic studies are addressed. In the case of active source, seismic waves are generated artificially, from the explosion of dynamite or a Vibroseis, for land surface surveys or using hydraulic cannons when the survey takes place on the ocean. In the case of the passive source seismic waves the source is natural, that is, from earthquakes.

In this work, the passive seismic method will be addressed as an important tool within geophysics. A tool that has a wide application in geothermal exploration. To do this, we will resort into a rough description of its application and particularly a case of Colombia, where it is proposed to use passive seismic exploration of geothermal resources.

INTRODUCTION

Seismological or passive seismic studies in different volcanic or geothermal areas have shown that seismicity can be associated to tectonic activity (local and regional) or the dynamics in the subsoil of geothermal fluids (magma, water and gas). In geothermal exploration, these studies are used as a tool for the evaluation of heat sources, fluid flow channels, deep hydrothermal activity, fluid migration, permeable zones and reservoir properties (Georgsson, 2009; Simiyu, 2009).

We describe studies using the passive seismic method depending on the type of data or information available, whose purpose will be for obtaining various physical parameters related to the area of study. First, using seismic records (raw data) which must be processed for interpretation and with which seismologist can conclude about the observed area of study. On the other hand, obtaining information and processing data from a catalog of seismic events that allows to advance in other types of interpretations of the area of interest. Finally, some analyses topics are described regardless of the origin of the data or the information available, and that are applied in the exploration of geothermal resources from the natural seismic activity.

TYPES OF STUDIES

Velocity models

Velocity models generated from seismic records (events or seismic noise) through inversion techniques, are a fundamental basis for various geophysical and geological analysis. These show the possible changes of lithology of the subsoil according to the contrast of seismic wave velocities, for example, of the velocity of the P wave and the S wave (Vp and Vs, respectively, Figure 1). The importance of these lie in the information provided from the structural and tectonic point of view, in addition to the location of seismicity, it is always important to have a velocity model that allows the adjustment of the epicenter and the focal depth of events. On the other hand, the obtention of a contrast among shear wave velocities V_s in depth is useful for the density of fractures analysis, that show areas of high permeability and that are potential targets for drilling high production wells (Simiyu, 2009).

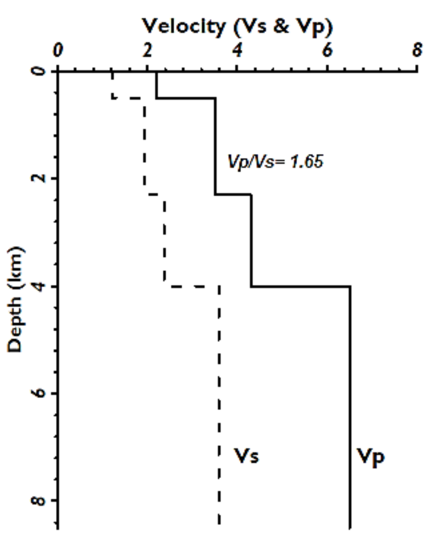

Figure 1. Example of one-dimensional velocity model in the Menengai volcanic zone in Kenya (Taken from Simiyu, 2009).

Determination of location and magnitude parameters of seismic activity

From the arrangement of a seismic network in the geothermal area of interest, seismic activity that is occurring may be recorded within and on the periphery of the network. For the cases of exploration, seismic instrumentation campaigns are temporary, that is, the time in which the equipment must be recording data is fixed according to the target that is being studied and considering the cost-benefit relation.

Once enough data has been acquired according to the observation time, the records are processed with the corresponding techniques of location, magnitude computation and focal mechanisms obtention. Finally, the catalog of seismic events is obtained, which generally consists of micro-seismicity events, events of small magnitude (M <3) that may be related to processes of geothermal underground interaction.

Microseismicity in geothermal zones allow to identify the trajectory of active faults and permeable zones in faults or fractures (when there are hydrothermal surface manifestations). The study of the spatial distribution of microseismicity gives guidelines for understanding the control that tectonism exerts over volcanic processes, or on the distribution of zones of fracture, and weakness that facilitate the flow of hydrothermal fluids (Curewitz and Karson, 1997; 2009; Simiyu, 2009; Faulds and Hinz, 2015). On the other hand, the distribution of the seismicity as the depth increases allow locating the Brittle-Ductile Transition zone (BDT) (Figure 2) of the crust, here begins the end of the cataclastic processes and the rocks of the crust tend to have a "ductile" behavior (Scholz, 1988, Helffrich and Brodholt, 1991, Dragoni, 1993, Best, 2003, Tanaka, 2004, Pluijm and Marshak, 2004, DeNosaquo *et al.*, 2009, Kissling *et al.*, 2010; Violay *et al.*, 2010; Suzuki *et al.*, 2014; Antayhua-Vera *et al.*, 2015). From this limit, the seismicity tends to decrease drastically due to the increase in temperature, depending on its proximity to a primary heat source, for example, in geothermal scenarios that do not show signs of hydrothermal surface activity, but that have indications of important magmatic activity at greater depths (> 5 km) as is the case of the enhanced geothermal systems (EGS).

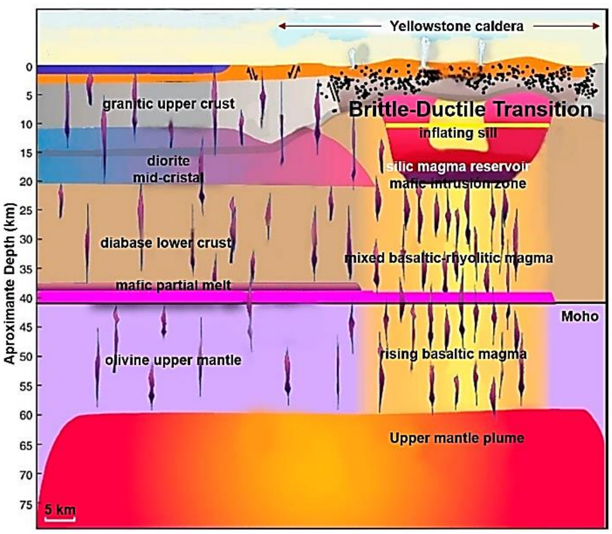

Figure 2. Scheme of the model of the Yelowstone volcanic complex, USA. Below the caldera we can see the Brittle-Ductile Transition (BDT) zone, where the seismicity decreases drastically (Taken from DeNosaquo *et al.*, 2014).

Attenuation of seismic waves

Basically, what is sought with these analyses is to know the behavior of seismic energy according to the environment where it is propagating and whose amplitude energy can be modified in its trajectory. For this reason, these types of studies are important because they also provide information on the subsurface structure of the area of interest, for example, if an attenuation analysis shows that P waves have greater attenuation than S waves, it may suggest a shallow crust partially saturated with fluids. Due to this behavior of the medium, the S wave continues to propagate but at a low speed, hence its attenuation is less than the P wave. Another case is the complete attenuation of the S wave, that could be used to predict the location of possible magma bodies or partial fusion chambers (Georgsson, 2009).

The techniques used for this type of studies are diverse (such as those that focus specifically on body waves as mentioned before) and go from the conventional ones, that work with the coda where the waveform of the seismic event finally decays, as it is the case of the quality factor coda Q (Qc; Aki and Chouet); to the most advanced ones based on seismic interferometry (Draganov *et al.*, 2010). Figure 3 shows an example of Qc mapping related to possible permeability behaviors in the volcanic and geothermal zone of Las Tres Vírgenes, Baja California, Mexico.

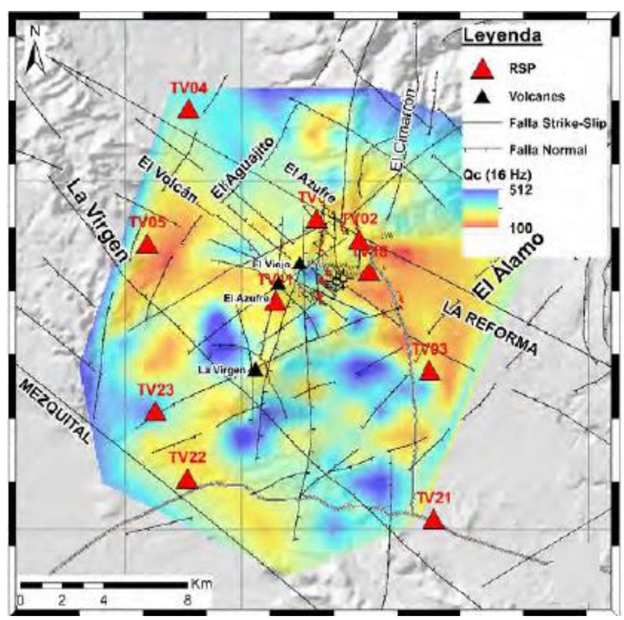

Figure 3. Map of iso-values of Qc in the geothermal field of Las Tres Vírgenes (Taken from Atatyhua, 2017).

Vp/Vs Ratio

The interpretation and analysis of the velocity ratio of the P and S body waves (Vp/Vs) characterizes qualitatively the properties of the medium through which these waves travel. The velocities of the seismic waves that pass through a medium with elastic properties that vary are affected and this can be observed in Vp, Vs or in both. These variations can be due to many causes such as the alteration of the rocks because of weathering and fracturing, as well as volcanic alteration or geothermal activity, among others.

Vp/Vs has traditionally been estimated by the Wadati method (Wadati, 1993, Figure 4). Majer and McEvilly (1979) made use of passive seismicity to study Vp/Vs in the region of the Geysers in California, finding that low values of Vp/Vs were related to a steam producing area. Wong and Munguía (2006) used the Vp/Vs ratio of the volcanic and geothermal field of Las Tres Vírgenes to estimate Poisson values ($0.22 \leq \sigma \leq 0.26$) obtained from Wadati diagrams, identifying partial saturation of thermal fluids within the materials from El Aguajito caldera zone and El Viejo, El Azufre and La Virgen volcanoes; they also demonstrated the correlation of hydrothermal activity with a well-defined trend of microseismic activity in these places. Simiyu (2009) performs a tomography of Vp/Vs values to relate them to the possible heat source of the Menengai caldera in Kenya (Figure 5).

The variation of the Vp/Vs ratios is associated with the phases of the reservoir fluid, where low values are related to a decrease of the P wave velocity in the area of low pore pressure, high heat flow, fracture and vapor/gas saturation within the field. It can also be found that these relationships can be a useful tool to monitor reservoirs in exploitation (Simiyu, 2009). In the Nevado del Ruiz volcano, Colombia, it was observed that low Vp/Vs values (1.3–1.6) in the upper part of the volcano, at depths of −3 to –2 km, are interpreted as the result of vapor accumulation within highly fractured zones of the hydrothermal system (Londoño and Hiroyuki-Kumagai, 2018).

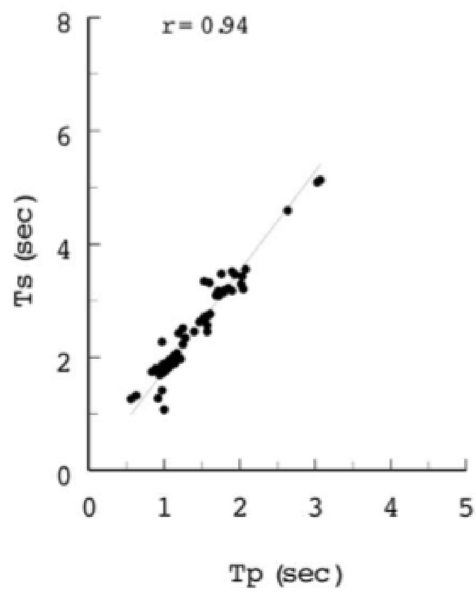

Figure 4. Example of a Wadati diagram for the central area of Las Tres Vírgenes (Taken from Wong and Munguía, 2006).

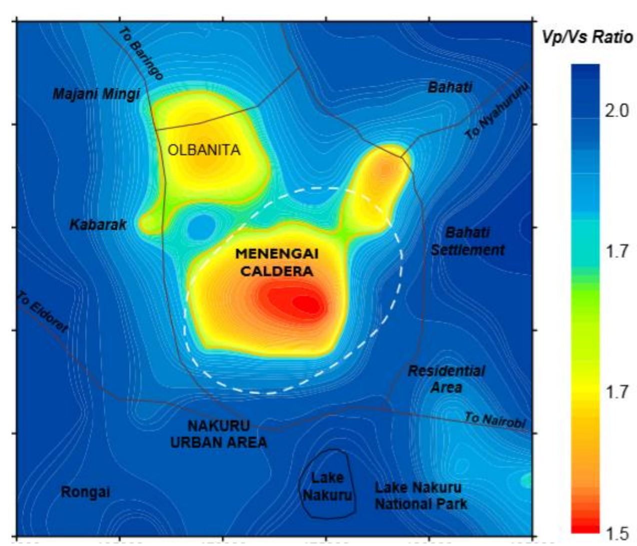

Figure 5. Map of Vp/ Vs values in the Menengai caldera, Kenya (Taken from Simiyu, 2009).

Focal mechanisms

As mentioned, seismicity or microseismicity in volcanic and geothermal zones can be associated with tectonic activity (local and regional) and fluid dynamics (magma, water and steam). The focal mechanism describes the orientation and sliding of a break in the crust for a specific seismic event (Havskov and Ottemöller, 2010) and its determination provides important information for interpreting the physical processes that have taken place in the focus region of an earthquake, allowing to know the corresponding state or regime of efforts that produces it (Cronin, 2010, Havskov and Ottemöller, 2010; Bormann and Wendt, 2012)

The distribution of focal mechanisms of seismic activity in these zones gives guidelines for understanding the control that tectonism exerts over volcanic processes or on the distribution of zones of fracture and weakness that facilitate the flow of hydrothermal fluids in geothermal systems (Boyd *et al.*, 2015; Antayhua-Vera *et al.*, 2015; Figure 6)

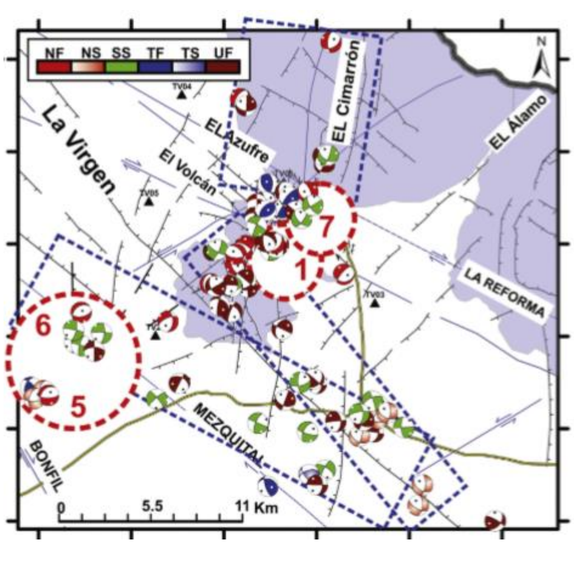

Figure 6. Distribution of focal mechanisms by zones in the volcanic and geothermal complex of Las Tres Vírgenes (Taken from Atatyhua et al., 2015).

Statistical seismology (*b*-value)

A relationship between the number of seismic events and the magnitude of seismic events, has been observed in seismically active regions of the world. In general, it has been found that there is an exponential relationship between the number of earthquakes and their magnitudes (Gutenberg and Richter, 1944). The frequency of occurrence of seismic events as a function of the magnitude is expressed as follows:

$$\log N = a - bM$$

Where N is the cumulative number of earthquakes with magnitude greater than or equal to M, a and b are positive real constant parameters, which characterize the seismic activity in a region with a given observation period.

The critical parameter from this relationship is the *b*-value that defines the slope of the straight line of the frequency-magnitude distribution that physically provides information about the origin of the seismic activity in a region (Zúñiga y Wyss, 2001; Wiemer y Wyss, 2002; Condorí y Pérez, 2016). The tendency of earthquakes to group in a certain range of magnitudes is considered a characteristic that marks the separation between the seismic activity of tectonic origin from the one of volcanic origin, for example, qualitatively the *b*-value close to 1 is associated with tectonic processes and indicate areas of homogeneous crust and high stress. However, in volcanic and geothermal environments these values are greater than 1, even close to 2. These anomalous *b*-values have been attributed to the heterogeneity of the medium (Mogi, 1963), decrease in the effective stress state (high pore pressure; Pearson, 1981), high thermal gradient (Warren y Latham, 1970), high degree of fracturing (McNutt, 2005), changes in the level of fluids (Wiemer and McNutt, 1997, Wyss *et al.*, 2001, Sánchez *et al.*, 2005, Legrand *et* *al.*, 2011, Viegas and Hutchings, 2011), and even with magma body cooling (Zollo *et al.,* 2002), reservoir permeability (Majer *et al.,* 2007), and water injection processes in the geothermal reservoir (Cornet *et al.*, 1997, Dorbath *et al.*, 2009, Maxwell *et al.,* 2009, Viegas and Hutchings, 2011; Bachmann *et al.,* 2012).

Figure 7 shows an example of a pseudo-3D tomography of the *b*-value of Los Azufres geothermal field in Mexico where the maximum *b*-value occurs approximately 2 to 4 km below the surface. The high *b*-values coincide with the highest temperature isotherm in this field, so this analysis is useful to identify sites with high temperatures or areas of heat rise, to locate new production areas, as well as to identify the approximate location of the heat source of the system (Cruz-Noé *et al.,* 2013).

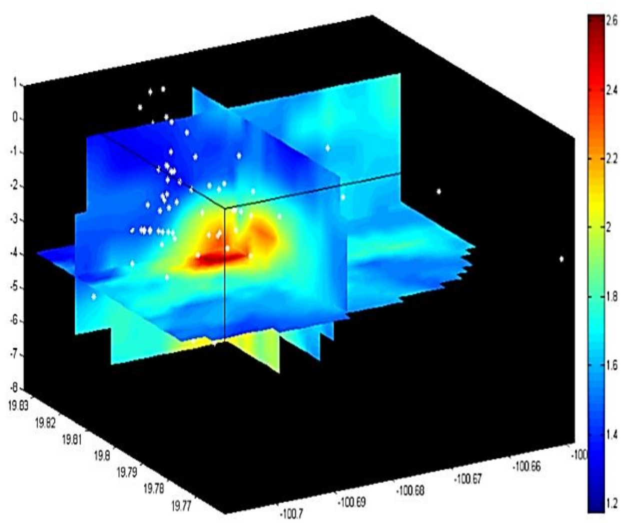

Figure 7. *b*-Value in the geothermal field of Los Azufres in Mexico (Taken from Cruz-Noé *et al.,* 2013).

Analysis of waveforms in time and frequency domain

One way of studying the seismicity of a region is to correlate the seismic signals with the physical processes that generate them (sources). For this, you can analyze the seismic records and identify certain patterns such as the waveform envelope in time and frequency domain. In the study of a volcanic or geothermal region, the seismic signals that are recorded may be different from those expected from a purely tectonic environment, since in volcanic regions the series of seismic events may occur due to the dynamics of fluids (magma, water or gas) or local tectonics. Figure 8 shows the types of seismic signals that can be expected frequently in volcanic structures based on what was documented by the authors Wassermann (2012), Zobin (2012) and Inza-Callupe (2014).

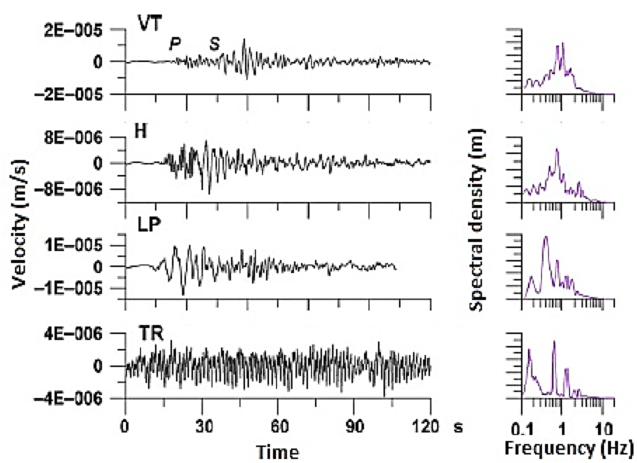

Figure 8. Types of seismic signals in volcanic structures, in time domain (vertical component of a seismometer on the left) and in the frequency domain (Fourier spectrum on the right). Volcano-tectonic event (VT); hybrid or multiphase (H); Long period (LP); Tremor (TR) (Taken from Zobin, 2012).

CONCLUSIONS AND RECOMMENDATIONS

In Colombia, the use of seismology or passive seismic in volcanic areas with geothermal activity has been focused on seismic vigilance, so it is suggested to benefit from its use for exploration purposes of geothermal resources with economic advantages for the country.

It is necessary to carry out instrumentation campaigns in specific areas of geothermal interest and not only limited to obtaining data or information from the volcanological observatories existing in the country. Having temporary seismic networks installed in areas of interest, allows a greater resolution of the observed and, eventually, more detailed studies.

The analysis of passive seismic studies depends on the type of data or information that is available, that is, whether it is raw data or information that results from their processing or through a microseismic catalog, for example, to determine the *b*-value of the study area and find possible relationships with areas in depth of high temperature.

The types of analysis described in this paper can also be applied in the production stage for geothermal field monitoring purposes, that is, passive seismic has a great advantage over other geophysical techniques in the sense of its permanent use in the whole process of the development of the geothermal project, being for this reason very profitable.

Finally, the combination of all geophysical methods with geology and thermal studies is important. The integration of all the information provided by all these disciplines, will make it possible to delimit geothermal scenarios in the best way, as well as obtaining a conceptual model of the system, coherent with reality. This will depend on whether an exploration campaign is successful and leads to the development of the geothermal project, and if so, its success can be measured by time, effort and the money saved.

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