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ANALYSIS OF SEISMIC ANISOTROPY IN LOS HUMEROS GEOTHERMAL FIELD, PUEBLA, MEXICO.

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ABSTRACT

This study presents the results from the analysis of seismic anisotropy in Los Humeros Geothermal Field, Mexico, correlating the parameters of anisotropy: polarization (θ) of the fast shear-wave qs1 and time delay (δt) of the shear-waves qS1 and qS2, with the tectonics and horizontal stress state in Los Humeros Field. By correlating and studying the phenomenon of birefringence or double refraction of shear-waves, we managed to watch matches in the directions of polarization (θ) and fracturing present in-situ. The analysis includes two study periods: 1997 to 2002 and 2004 to 2008, in which we identified three areas of seismic anisotropy with the same direction of stress, fracturing and/or faulting: zone with efforts in NE-SW 20^0 direction, mainly due to regional tectonic stresses, zone E-W (NE-SW 85 °), an area with high structural complexity, mainly produced by the variation of the stress in the E-W direction, however most of the faults are inflicted in these directions, and finally the zone NW-SE 45 ^{0}, produced by stress with less tectonic influence, according to the associated fractures and polarization analysis in the stations.

INTRODUCTION

Los Humeros Geothermal Field is located in the Eastern Trans-mexican Volcanic Belt (CVTM) in limits with Puebla and Veracruz. The Comisión Nacional de Electricidad (CFE by its Spanish acronym) installed in 1997 a Permanent Telemetric Seismic Network (RSTP by its Spanish acronym) which consists of six triaxial digital seismographs (S01, S02, S03, S04, S05 and S06) distributed around the geothermal field (Lermo *et al*., 2008).

Los Humeros Field (Figure 1) is currently the fourth field of production in Mexico with 40 MW distributed in eight units with a production capacity of five MW each one of them, which are fed average of 20 producing wells per unit.

Seismic records from 1997 to 2008 were selected to analyze seismic anisotropy. In this paper about 79 earthquakes were recorded in at least five stations and they were located near the injector wells I38 and I29 within Los Humeros Field. The seismic anisotropy parameters were obtained by analyzing preferential polarization (θ) and time delay (δt) of shear-waves qS1 and qS2 from earthquakes selected at each station, finally anisotropy parameters were correlated with tectonics and principal stresses within Los Humeros Geothermal Field.

Studies from García (2006) demonstrate that seismic anisotropy is useful to detect preferential fracturing directions, which can be interpreted as zones of fluid flow, this information would identify areas favorable to drilling and production wells.

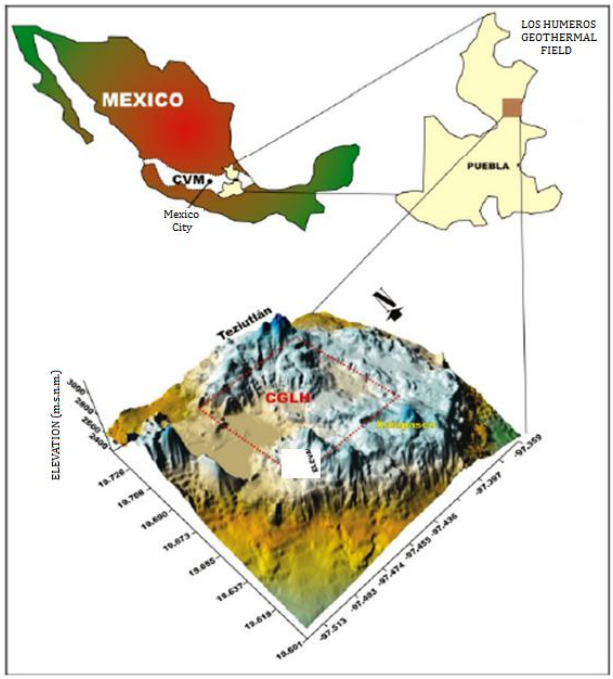


Figure 1: View of Los Humeros Geothermal Field (modified from Lermo et. al, 2008).

Geology

According to geological studies from Arellano *et al*., (2000) and Cedillo (1997), seismic reflection (COMESA, 1998) and gravimetric studies (Campos-Enríquez and Arredondo-Fragoso, 1992) Los Humeros Field is a caldera whose stratigraphy is comprised by nine main layers. Geochemical studies (Barragán *et. al.,* 1988), studies of log wells and core analysis (Arellano *et al.,* 1998) show the presence of two basins at different depths, the shallower at 1.5 km with 280°C temperature and the deeper to 330°C. The shallower basin is Dominant Liquid and the deeper is Dominant Steam (Arellano *et al.,* 2000).

Permeable formations are andesite of augite, andesite of hornblende. Basalt and marble (near basement) are the less permeable zones and possibly are the zones of the two types of basin.

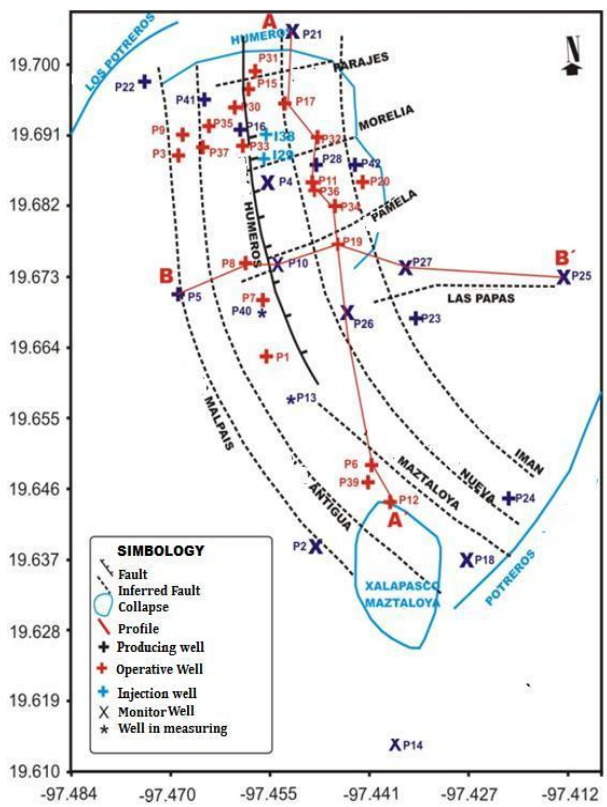


Figure 2: The map shows two fault systems: NW-SE formed by: La Antigua, Malpais, Humeros, Iman and La Nueva faults, the other system in NE-SW direction formed by: Pamela, Arroyo Grande, Parajes and Morelia (modified from Lorenzo, 2002).

In Los Humeros Field were detected two faults systems (Seismocontrol, 2005). The first consists on Malpais, La Antigua, Maztaloya, La Nueva, Iman and La Cuesta faults, they tend in NW-SE direction, the latter two are observed on the surface and the rest were inferred by geological and geophysical methods. The second faults system is oriented in NE-SW direction: Pamela, Parajes and Morelia faults (Lorenzo, 2002), while Las Papas and Las Viboras faults are oriented approximately E-W direction (Figure 2).

DATA AND EQUIPMENT

We selected 79 seismic events from 1997 to 2008 that have the following characteristics: duration magnitude [1-3.5 Md], detected in at least five stations, with location errors less than 2 km of surface and depth, Root Mean Square (RMS) less than 1.0 , especially those seismic events that have origin in the center of Los Humeros Field with phases P and S waves easily identifiable, in order to optimize the hypocentral location (Antayhua, 2007).

In this study, the time readings of arrival were performed with an accuracy of 0.01 s for P wave and 0.05 s for S wave. The ratio Vp / Vs = 1.76 used for localization was obtained by Wadatti curve constructed from the arrival times of P and S waves (Antayhua, 2007). The velocity model corresponds to that proposed by Lermo *et al.,* (2001) and the seismic reflection profile by COMESA (1998). The P wave velocity (Vp) and the equivalent depth of nine strata of Los Humeros Field were obtained following the methodology described by Dix (1995). The equation used to calculate the duration magnitude of Los Humeros Geothermal Field events, is proposed by Antayhua (2007) in equation (1).

$$Md = -0.1285 + 1.6283 \, Log10 \, (T) + 0.0487 \, (D) \quad (1)$$

Where: Md is the duration magnitude in degrees corrected from the equation proposed by Lee *et al.* (1975), T is the total duration of the seismic event in seconds and D is the epicentral distance in kilometers.

The location of seismic events was performed with the subroutine hypocenter, from the program SEISAN version 8.0 (Havskov and Ottemoller, 2003). This program uses as input data: station name, geographical coordinates (latitude and longitude), altitude, reading times of the P wave (Tp) and S waves (Ts) arrivals, duration of the earthquake, velocity ratio (Vp / Vs), velocity model (Table 1) and an equation for calculating the duration magnitude.

Table 1: Velocity model in Los Humeros Geothermal Field (Hurtado, 2001.)

Depth (km)	Vp (km/s)
0.00	1.24
0.24	1.94
0.65	2.85
1.25	3.54
1.79	3.69
1.93	3.90
2.13	4.14
2.37	5.18
30.00	6.00

CFE set up a Permanent Telemetric Seismic Network (RSTP), since December 1ts, 1997, consisting of six seismic stations (S01, S02, S03, S04, S05 and S06). The RSTP monitors an area of 20 km^2. In 2004 the stations: S01, S02, S03 and S04 changed their places due to problems of distance and equipment signal, except S05 and S06 stations, which stayed in the same position.

Each station has a digital recording seismograph of acceleration Altus K2 with a resolution of 16 bits. The recorder is attached to three speed sensors Kinemetrics Ranger SS-1 type short-period (1s) in its three components, two horizontals (N-S and E-W) and a vertical (Z).

ANISOTROPIC MEDIUM

The birefringence or double refraction is a phenomenon that occurs when the shear-wave is refracted into two shear waves with different speeds and mutually orthogonal polarizations: qS1 fast and qS2 slow (Vazquez, 1994). Birefringence will not occur whether incidence is normal or parallel in the anisotropic body (Crampin and Lynn, 1989). The time delay between fast and slow waves depends on the thickness of the anisotropic body, fractures density, S wave incidence to anisotropic body (Figure 3).

The maximum regional stress tends to open or align the fractures. Through seismic anisotropy analysis, the direction of the anisotropic medium and stress can be determined. (Crampin, 1985)

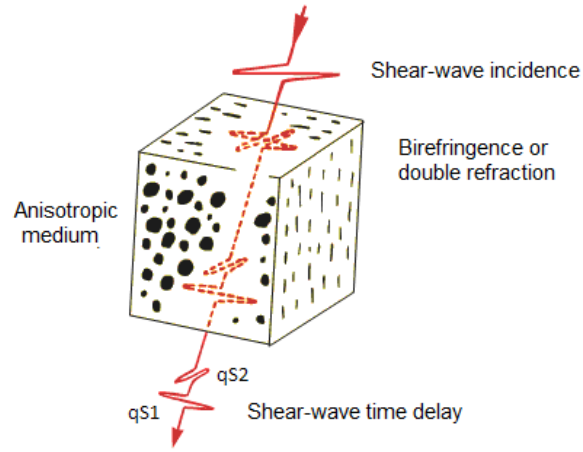


Figure 3: Shear wave incidence in an anisotropic medium produces the phenomenon of birefringence: time delay and orthogonal polarizations between qS1 and qS2.

METHOD FOR CALCULATING SHEAR-WAVE POLARIZATION (Θ) qS1

Chen *et al.*, (1987) developed a procedure to measure and distinguish the polarization of shear-wave from seismic events. Vazquez, (1994) modified this procedure, following the next method (Figure 4):

-Rotation of the seismograms in radial and transversal components. We showed the time delay between fast wave (qS1) and slow wave (qS2) of a local event in HU5 station.

-Analysis of particle motion. Hodograms in Figure 4 a) hodogram shows the movement of the P wave, b) arrived of fast shear-wave qS1 which has a greater amplitude and preferred direction (indicated by an arrow) and c) the total of the previous time.

-Measurement of shear-wave polarization qS1. We measured azimuthally the angle of shear-wave qS1 to know the preferential polarization, once detected, coordinates should be returned to North-East direction, this last rotation determines the preferred direction of the anisotropic medium.

This procedure is performed similarly in the other stations and seismic events to obtain a preferred direction.

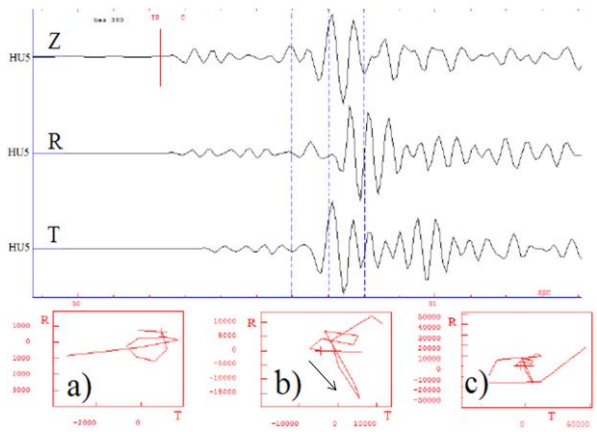


Figure 4: Seismic record from HU5 station shows different time arrivals in the radial(R) and transverse(T) components. a) Hodogram of P-wave, b) Hodogram of shear-wave, shows preferred polarization and c) Hodogram covering the previous two sections.

METHOD FOR CALCULATING TIME DELAY qS1-qS2

To measure the time delay of shear-waves qS1 and qS2, qS1 should be viewed in shear-wave arrival window, and then we perform the following procedure:

1) Measure the first direction movement (α angle) of the shear-wave qS1, in the particle diagram or hodogram of the horizontal components (N and E).

2) Rotate the components in α angle direction.

3) Calculate the maximum cross-correlation coefficient from the components rotated.

4) The maximum cross-correlation coefficient is the time increment (δt), which is considered as the delay between shear-waves qS1 and qS2.

5) The slow component qS2, increases with respect of qS1 (δt).

6) The components are rotated back to the North-East system; the corrected particle diagram is plotted showing a higher linearity.

This method is semi-automatic because the fast shear-wave qS1 arrival is selected visually by examination of the successive time windows. The cross-correlation is an operation that automatically determines the time difference (Figure 5).

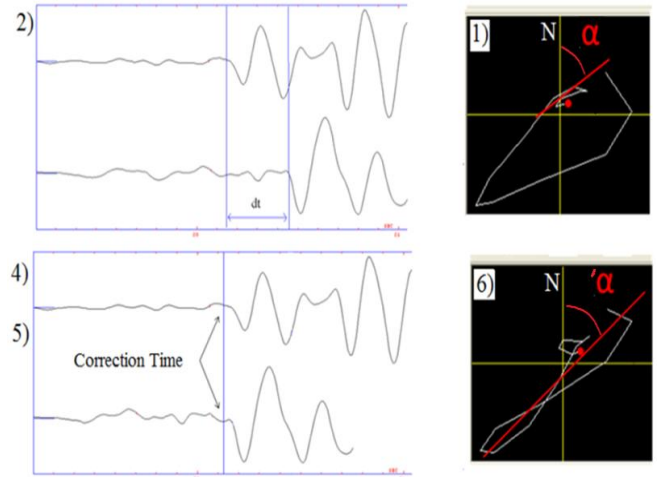


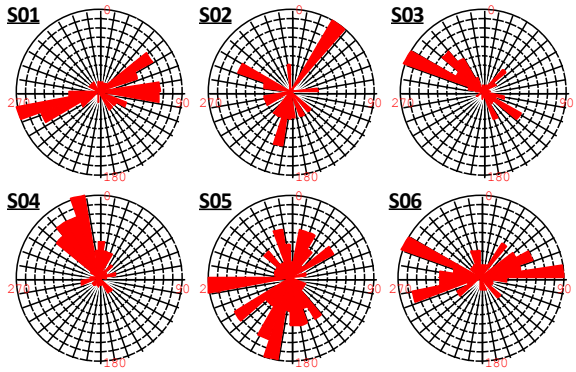
Figure 5: Methodology for anisotropy parameters. 1) Measurement of azimuthal α angle, of fast shear-wave sqS1, 2) Rotation in α of horizontal components, 4) Cross-correlation, 5) Measuring and correction of time delay between shear-waves in δt time and 6) Rotate back to the N-E components and the corrected particle diagram is plotted showing a higher linearity.

RESULTS

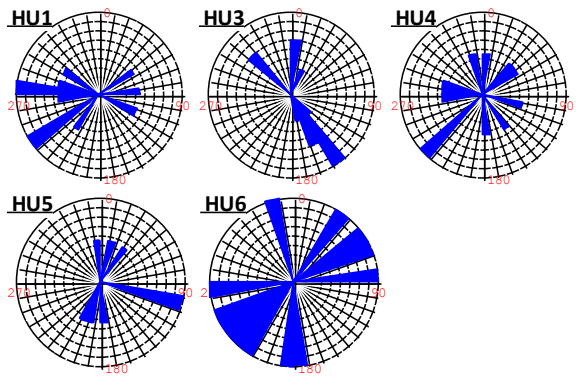
To determine the seismic anisotropy in Los Humeros Geothermal Field was necessary to calculate the parameters: polarization (θ) and shear-wave time delay (δt) of the 79 local events previously selected. The values of the parameters vary in each station due to their distribution within Los Humeros Field.

The analysis of seismic anisotropy parameters was separated into two periods, the first 1997-2002 and second 2004-2008, this difference was performed due to the change in location of the stations in 2002. Only HU5 and HU6 stations (S05 and S06 during 1997-2002) retain their locations.

Figure 6 shows the results of polarization directions from shear-wave qS1 in rose diagrams by stations, the largest amplitudes represent a higher occurrence in polarization direction. The rosettes show polarizations of 1997-2000 in red and the 2004-2008 in blue.



Station	Num. Measurements
S01	59
S02	18
S03	63
S04	64
S05	65
S06	60



Station	Num. Measurements
HU1	11
HU2	--
HU3	12
HU4	12
HU5	8
HU6	12

Figure 6: Rosettes on the top for the period 1997-2003 show the polarization directions of shear-wave qS1 and its table with the number of measurements to each station. Rosettes on the bottom for the period 2004-2008 with its table.

In the area of the S01 and HU1 stations, stresses are aligned in E-W direction and slightly NE-SW 85°, possibly fractures associated with stresses of the Trans-mexican Volcanic Belt (CVTM) (Ferrari *et al.*, 1994, Suter, 1991, Cserna *et al*., 1988). The S06 station showed preferential polarity almost E-W systems possibly due to fracturing in the direction coinciding with Las Papas fault.

The S02 station showed polarization in direction NE-SW; coincides with stresses around the CVTM (Suter, 1991, Cserna *et al*., 1988).

The S05 station has polarity N-S and NE-SW directions; the first with a tendency to Los Humeros Fault, while the second is associated with a regional stress NE-SW along the CVTM (Suter, 1991, Cserna *et al*., 1988). The S03, S04 and HU3 stations have preferential NW-SE polarization direction; contrary to regional stress possibly associated to La Antigua and Malpais faults. HU4 station was relocated near the center of Los Humeros Field and changes its polarity to NE-SW direction, coincident with faults in the same direction.

We observed that the polarizations of stations; correlated with the tectonics, regional faults and fractures direction. The S01, S06 and S05 stations have a NE-SW polarization coinciding with regional stresses and S03 and S04 stations have perpendicular direction NW-SE.

Zoning

In Figure 8 we proposed a zoning of faults and fractures, areas with the same direction of faults, fractures and stresses.

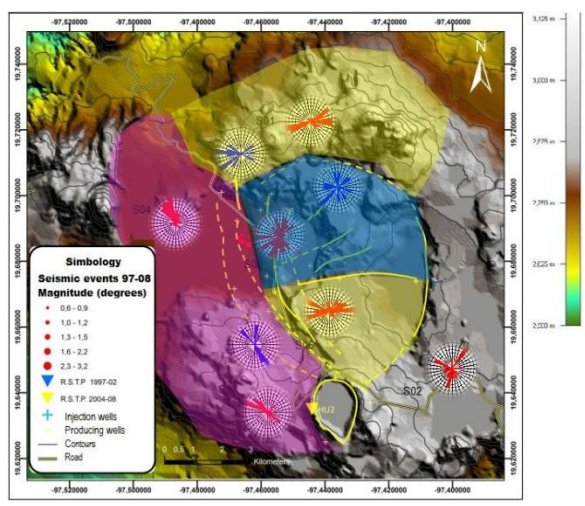


Figure 7: Altimetry map showing the proposal zoning, areas of the same color represent faults, fractures and stress in the same directions, Zone A (pink area, NW-SE) direction), Zone B (blue area, NE-SW) and Zone C (yellow area, E-W).

Zone A, the distribution of polarization in S04, S03 and HU3 stations indicate preferential NW-SE direction; the area is bounded on the West by La Antigua and Malpais faults, to the South by the

Xalapasco Caldera to the North by La Cuesta fault, who tends N-S and to East by Los Potreros collapse.

Zone B, HU4 and S05 stations tend to NE-SW direction; coincident with the stress mentioned above by Ferrari *et al.*, 1994 and Cserna *et al.*, 1988, have influence from the Trans-mexican Volcanic Belt (CVTM), this area occupies the center of Los Humeros Geothermal Field and is limited to the East by Los Potreros collapse , while in the South by Las Viboras fault, where the direction of fracturing change, and finally this area is bounded on the West by La Antigua fault, also the limit of the Zone A.

Zone C, includes two areas in Los Humeros Field, S01 and HU1 stations with preferential direction E-W, relating to stresses mentioned by Ferrari *et al.*, 1994; indicating that there are E-W stress in this region of CVTM and additionally the station S06 showed a clear trend in the same direction, probably due to Las Viboras fault and fracturing in this direction.

We concluded that Los Humeros Geothermal Field is influenced by stresses in E-W direction (stations S01and HU1) according to Ferrari *et al.*, 1994. In contrast, Suter, 2001 and Cserna *et al.*, 1988 found compressive stress in NE-SW direction and several areas of CVTM, including Los Humeros Field (S05, S02 stations and additionally HU4) in the central Zone B. Finally, those tectonic stresses generate faults and fractures parallel and perpendicular directions watched in Zone A (pink area, S04, S03 and HU3 stations).

Graphics qS1-qS2

Stations S03 and S04 (Figure 8) have two time delay intervals, two possible anisotropic zones, the first between [0.0 - 0.02 s] which is interpreted as an anisotropic volume, the other set of values [0.05 - 0.09 s] indicates another anisotropic zone with greater difference of the shear-wave.

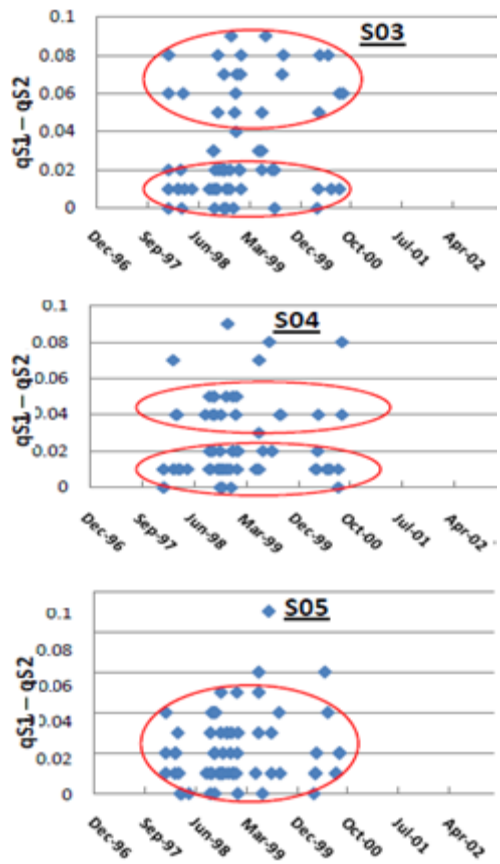


Figure 8: Graphics of time delay qS1-qS2 (seconds) vs. Time (Months-Years) of the stations for the period 1997-2002. The zones of high seismicity and greater range of time delays is observed in red ellipses indicating that the main accumulations represent areas of anisotropy.

CONCLUSIONS

Analyzing the anisotropy parameters: polarization (θ) and time delays (δ) of shear-waves qS1 and qS2 from the 79 seismic events in 1997-2002 and 2004-2008, we identified three areas of anisotropy with different directions in Los Humeros Geothermal Field:

-NE-SW 30° direction is detected in S05 and HU4 stations in the center of Los Humeros Field coinciding with regional stresses studied by several authors; this area has a structural complexity due to structures in NE-SW (N-S from Los Humeros fault and E-W from Las Papas fault).

-NE-SW 85°, E-W, direction is detected in S01 and HU1 stations from the North and S06 station from the center of Los Humeros field.

-NW-SE 45° direction is detected in S04, S03 and HU3 stations, matching the location of La Antigua and Malpais faults, suggesting that the polarization of the shear-wave qS1 is governed by these fractures.

The polarization (θ) is the parameter that distinguishes the direction of anisotropic bodies, while the time delay (δt) indicates its presence, however the latter is more difficult to interpret due to factors such as variation of incident angle, thickness and density of anisotropic medium. Zoning proposes areas with the same stresses and fracturing direction and possible flow fluid in this direction.

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