Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

3D Conceptual Model of Domo San Pedro Geothermal Field - Nayarit, Mexico

Violeta Mirthala REYES OROZCO, David AVALOS TAPIA, Julio GARCIA TIRADO, Esteban RODRIGUEZ PINEDA, Fernando OCAMPO AGUILAR

Km 12 Carr. Chapalilla-Compostela. San Pedro Lagunillas, Nayarit. Mexico. CP 36800

vreyeso@gdragon.com.mx; reyvi11_11@hotmail.com

Keywords: Surface exploration, Geology, Geophysics, Geochemistry, Lithology, Model, Calcite, Mineral deposition, Mechanical workover, Acid workover

ABSTRACT

The Domo de San Pedro geothermal field is located in the state of Nayarit in central western Mexico. It is developed and operated by Grupo Dragon, the first private company in geothermal energy generation in Mexico. Until 2016, nine borehole wells have been drilled in the field and currently have an installed capacity of 35.5 MW. It is composed of two backpressure units of 5 MW each and one condensing flash power plant of 25.5 MW. The region of San Pedro is located within the Compostela graben and the center of a structural depression caused by the intersection between N-S, NE-SW, NW-SE and E-W oriented faults. This is a complex asymmetrical depression developed during the Late Miocene and Pliocene. Our conceptual model has been constructed from the data generated during the exploration stage and also already in operation. This paper will describe the 3D conceptual model made by the Department of Geoscience to obtain a drill target. The 3D model integrates geology, well data, geophysics, geochemistry, temperature and pressure reservoir, passive seismic, among other data to bring an understanding of the subsurface. Also, the study of well production, the information that was studied using Leapfrog as tool in the beginning of this case, the design of the chemical intervention and the preliminary results are discussed.

1. INTRODUCTION

The Domos de San Pedro geothermal field is situated 5 km from the municipality of San Pedro Lagunillas as shown in Fig. 1., about 60 km south-east from the town of Tepic, in the western state of Nayarit. The Domos de San Pedro is the first private company in geothermal generation in Mexico, developed and operated by Grupo Dragon. Nine wells have been drilled in the field and currently has an installed capacity of 35.5 MW. It is composed of two backpressure units of 5 MW each and one condensing flash power plant of 25.5 MW.

In the Domos de San Pedro geothermal field, four different formations were recognized according to their stratigraphic position, age and composition. A brief description is presented for each unit, starting with the youngest units from the late Pliocene to the Quaternary, to the ancient Cretaceous-Paleogene basement.

On the volcanic deposits, dacitic and rhyolitic flows (0.6 -0.1 Ma) with a thickness above 700 m were placed. including pumicite, glass and banded rhyolite. The San Pedro del Pleistocene dacitic formation is present with dacitic colluvion and dacites. Remains and avalanche flows have occurred around the dome and extend to the southeast.

The andesites and dacites of the Pliocene (4.93.8 Ma) have an approximate thickness of 150 m. and rest on the andesitic lavas of the Miocene. Both rocks are porphyric with plagioclase phenocrystals predominantly in the andesites with some quartz phenocrystals in the dacite. Mafic minerals include pyroxene, hornblende and biotite, possibly hornblende pseudomorphs. This unit appears to be the stratigraphic seal layer of the geothermal reservoir.

The Andesitas del Mioceno unit (13-8 Ma) includes andesites, basaltic andesites and basalts. The bodies of riodacites and dacites enter them. This unit has a thickness of 1,250 m. and it is more altered than the overlying unit, so the original lithological and mineralogical characteristics are less common. However, the main type of rock is expected to be mainly porphyric with plagioclase phenocrystals, and to a lesser extent amounts of pyroxene in any unaltered rock.

Granodiorite and Diorite from the Late Paleocene Cretaceous (75-56 Ma). These units are associated to the basement of the Jalisco Block (BJ), it has a thickness above 3700 m where it has been drilled. This granitic complex is associated with the reservoir of the geothermal system due to secondary permeability due to faulting in the area of interest. The BJ contains different magmatic pulses composed of granite, granodiorite, tonalite that have been cross by aplite, diorite, and andesite or dacite feeding dikes of the most recent units.

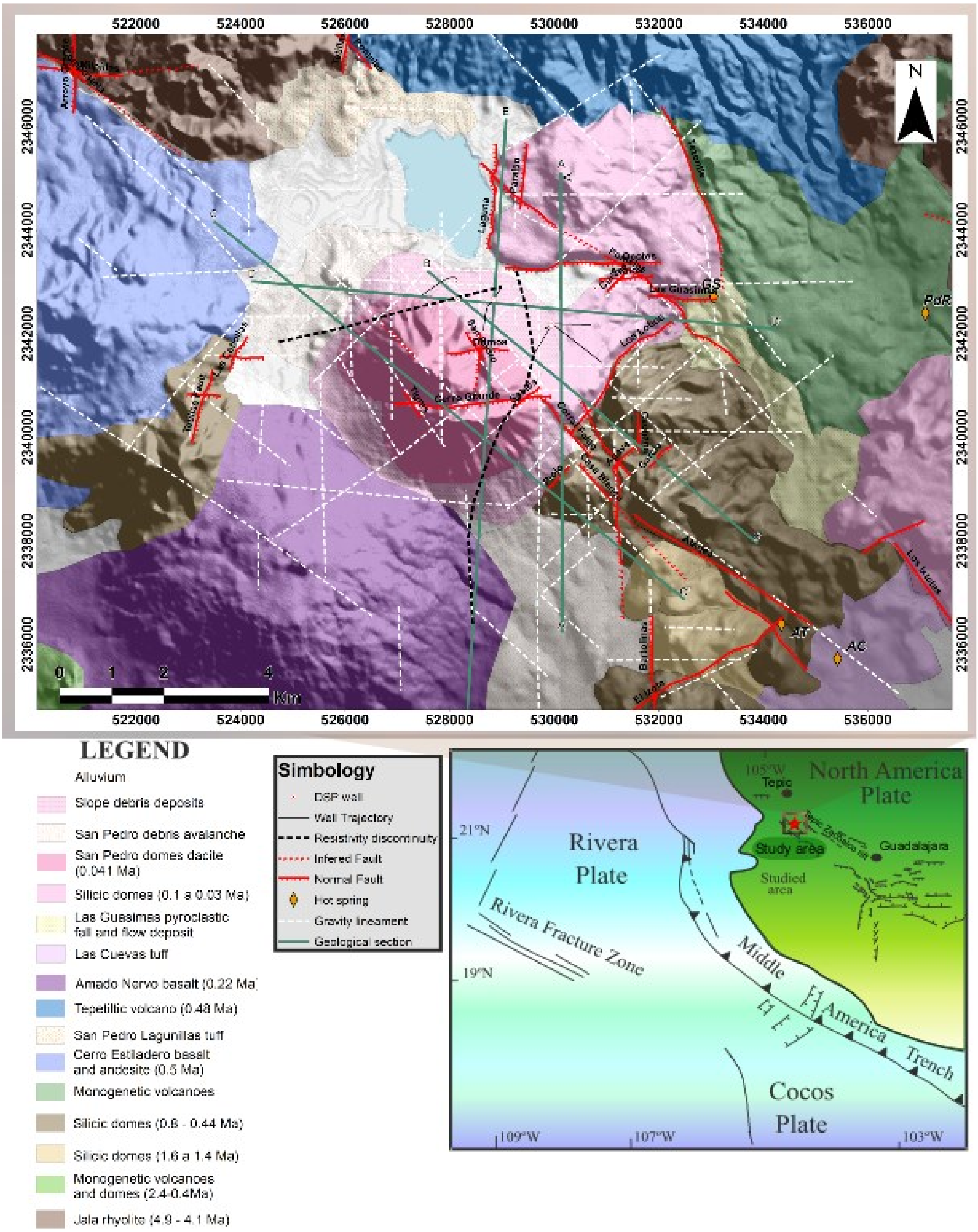

Figure 1: Location of Domos de San Pedro, Nayarit, Mexico. Structural and geological map of the study area with inferred faults based on the previous gravimetry and resistivity discontinuity. Hpt srping: AT; Agua Tibia, AC; Agua Caliente, GS; Guasimas, PdR; Puerta del Rio.

2. HYDROTERMAL ALTERATION

In general, the high temperature geothermal field mineralogy can be divided into the main hydrothermal mineral zones with increasing depth: argillic, propylitic and high temperature propylitic / potassium. The phyllic alteration zones can also be found in the propylitic zone particularly close to the structures.

The propylitic alteration in the rock that contains the reservoir is the intrusive complex of the Jalisco Block (BJ), it is abundant in areas of faults and in the contact areas of the levees located in this same fault in the northern region of the Domo de San Pedro. In the contact areas of andesitic dikes, these can be found from chloritized to potassium alteration, to an advanced biotitization alteration. There is a relationship with faulting with almost all permeable areas. For the deep permeable zones in the wells of the East zone they are in the contact of the diorite and the granite at depths of 900 to 1100 and in the North region in zones associated with faulting.

An assembly of chlorite, albite, calcite, pyrite, illite, garnet, sericite and quartz is representing the propylitic zone, where the epidote tends to be abundant on the northern flank of the San Pedro Domes in wells SP01-SP04 (Figure 2) and scarce to zero in the well zone SP05-SP08. The formation styles present are by replacement of primary mineral phases and by direct deposition. The latter is due to a chlorinated sodium free fluid with high mobility and consequently very depositing in faults, microfractures or fractures.

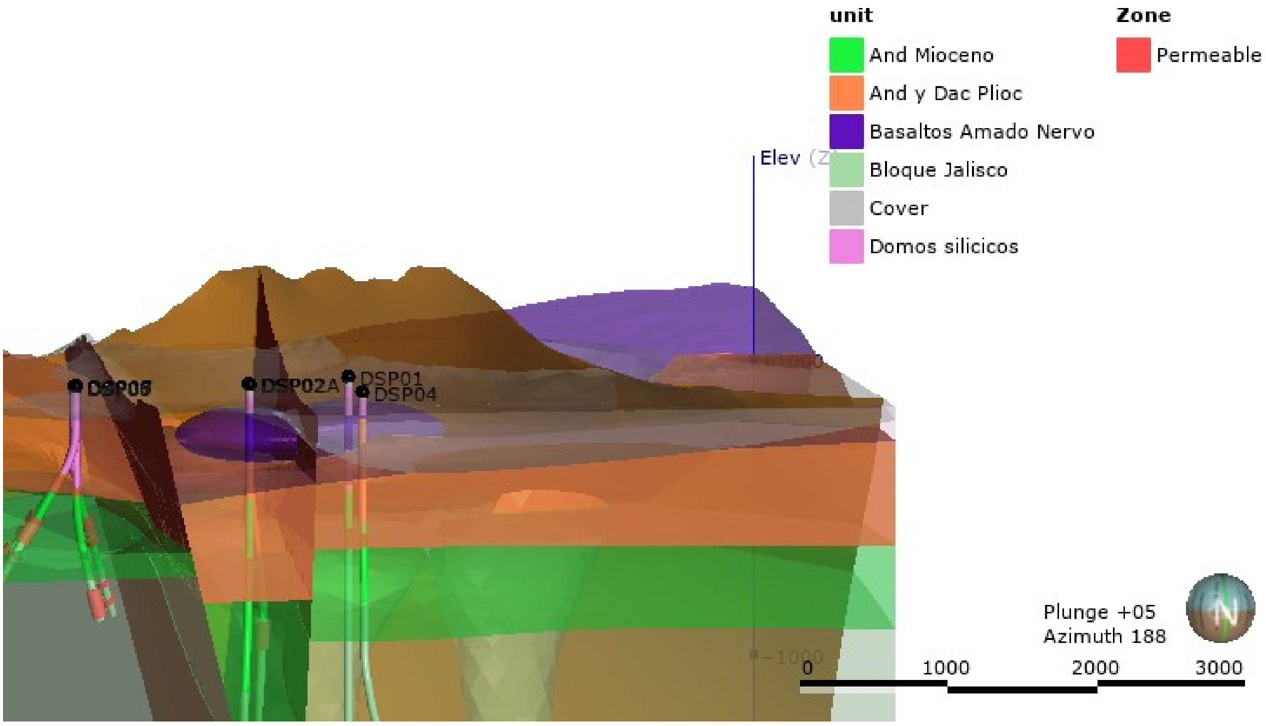

Figure 2: 3D Model of permeable zones in the wells.

It is recognized that the top of the reservoir can be defined at the minimum depth where the epidote occurs. In the wells of the north zone (SP01, SP02, SP02A, SP03 and SP04) the first appearance of epidote is well above the Isotherm at 240 ° C. The upper part of the reservoir, at an isotherm of 240 ° C, has no distinctive mineral marker and has a general set of propylitic hydrothermal alteration in permeable areas, but may also have silicified rocks with a quartz, clay set (most likely illite) and opaque.

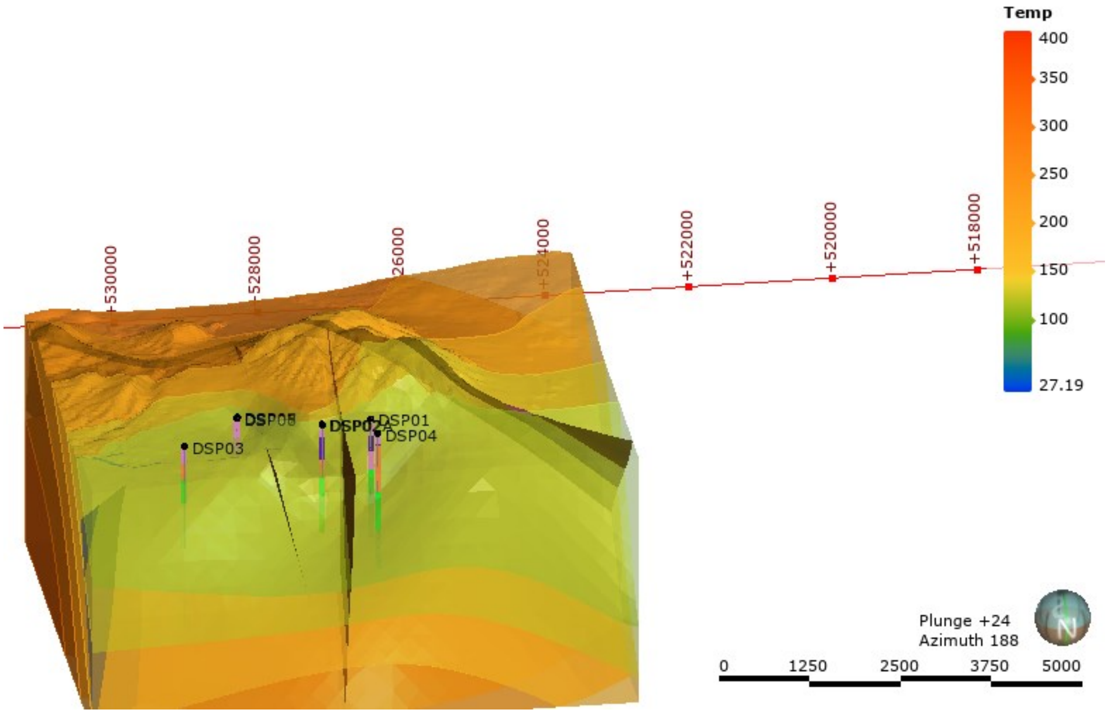

Figure 3: 3D Model shown isotherms in the wells.

In the wells SP05, SP06, SP07 and SP08, the appearance of the epidote is at 985 m MD, where there is a minimum reservoir temperature of 260 ° C. In the northeastern zone, propylitic alteration is associated with lithological contact with diorite with intense hydrothermal alteration. In the northern zone, the diorite is unaltered and can observe its original structure. In these wells it appears mainly in the feeding zones platy calcite, wairakite, quartz in druse, tourmaline, tremolite, magnetite and adularia. This association possibly reflects the presence of a gas layer in the upper part of the reservoir, where the presence of CO2 is too high to form an epidote, which would cause the calcite to be favored above the epidote and an alkaline tendency hydrothermal deposition. The adularia is an indication of boiling and is mainly found in well SP06. The secondary biotite where it is associated with granular quartz veins can be part of a potassium zone with presence of magnetite and potassium feldspar.

There is a relationship with the appearance of diorite in the discharge zone established in wells SP05-SP08 with almost all permeable areas. In the East, the interval in which the most superficial occurrence of the diorite is found corresponds to the shallow range of the permeable zones. Permeable areas may also have silicified rocks with a set of quartz, clay (most likely illite) and opaque.

Phyllic alteration is found when the amount of chlorite and albite decreases and when the composition tends to be a set that contains quartz, clay (illite) and opaque. Quartz is the most common mineral in veins with a mixture of prismatic and granular textures, with the exception of calcite in the SP04 well. Calcite is in granular texture and a rare platy calcite at 2380 m in well SP04 where it is partially replaced by clay (most likely illite) and fine prismatic quartz crystals. There are also veins of calcite with intercalated quartz, opaque, clay and chlorite.

The argillic zone (clay layer) occurs on a propylitic zone and occurs in the Miocene andesites, which can be seen with hematization, silicification, chloritization and argillic alteration by replacing plagioclase. The shallowest argillic zone is found in recent rhyolites. Clay is also highly developed in the pyroclastic underlying Pliocene. On the other hand, in the andesites of the Miocene it is where the greatest alteration is found by argillitization in the rock being with an average thickness of 500 m, where it is present in illite-smectite and illite, as well as, hematization and silicification. The argillic alteration is considered to function as the seal layer of our reservoir, limiting the reservoir stored in the granite and granodiorite of the BJ, as well as in the contacts with the diorite.

Another particularity observed in the Miocene andesites is the presence of potassium alteration in this rock, considering that it is a fossil alteration due to the depth where we currently find the geothermal fluid.

3. STRUCTURAL GEOLOGY

The Domo de San Pedro geothermal field is limited mainly by the NE-SW faulting, as well as the existence of conductive structures of the fluid, which most likely would be NW-SE and EW faulting and with possible suspicion the NS fault. Hosting the geothermal fluid in the granite-granodiorite complex of the Jalisco Block, which is confined by a layer of clay which alters the andesites of the Miocene and knowing that the permeability zones are associated with the faulting that affected said plutonic rock, where the major propilitic alteration associated with geothermal deposits of high enthalpy is presented. The E-W orientation related mainly to the Guasimas fault and thermal springs to the SE of the field conducted in NW-SE faulting, suggest that hydrothermal fluids may be draining along EW structures. To the Northeast of the geothermal field and to the south-east in NW-SE structures, without evidence that the NE-SW faulting serves as a means of transport, if not as a limiter of the geothermal system.

To the SE of the prospect, the rhyolitic and dacitic domes are clearly located along the NW-SE direction. Therefore, the distribution of these domes is indicative of an environment limited to an extensional regime NE-SW. In addition, the location of the springs is restricted to a discharge with EW orientation related mainly to the Guasimas Fault and thermal springs to the SE of the field conducted in NW-SE faulting, suggesting that hydrothermal fluids may be draining along E-W structures. Northeast of the geothermal field and south-east in NW-SE structures, there is no evidence that the NE-SW faulting serves as a means of transport.

Middle Miocene N-S faults reactivated during the Pliocene and NE-SW work as a reservoir boundary, the eastern flank of the domes is limited by the NE-SW fault system with a dip south-east toward Agua Caliente and Agua Tibia springs.

The N-S faults of the middle Miocene were reactivated during the Pliocene, and the NE-SW faults act as the boundary of the reservoir. The east flank of the domes is limited by a fault NE-SW with dip to the southeast in the direction of the springs Agua Caliente and Agua Tibia, this fault is Los Lobos Fault. The western flank of san Pedro domes is limited mainly by a system of N-S faults with a dip to the east, which disappear to the center of the graben.

To the SE of the prospect, the rhyolitic and dacitic domes are clearly emplaced along a NW-SE direction. Therefore, the layout of these domes is indicative of an environment constrained by an NE-SW extensive regime. Additionally, the location of the Agua Caliente and Agua Tibia thermal features to the SE of the field, suggests that the hydrothermal fluids might be drained along extensive NW-SE structures.

Faults with orientations E-W are also present and are very frequent considering a secondary system derived from the dominant regime of extensional stress NW-SE Pliocene. These faults become relevant because they are observed crossing the northern flank of the Domes of San Pedro as part of the same system. Likewise, in the geophysical analysis, it is identified by gravimetry (Boguer residual with Gaussian high pass filter and Euler deconvolution), magneto-telluric profiles and passive seismic that this system is a deep faulting in a range of 2.5 km and most likely it is affecting the reservoir rock. Another E-W fault is found cutting the Domes of San Pedro in its central part, this E-W fault is significant and is also inferred by gravimetry, however, it is not clear from the geophysical analysis whether this fault is shallow or is also deep.

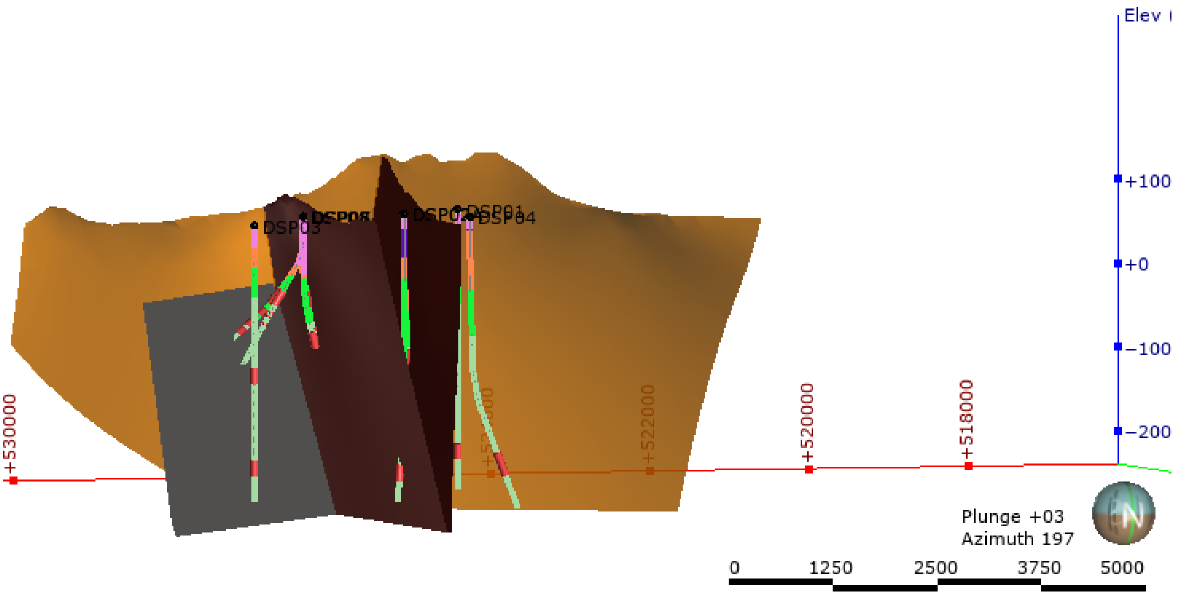

Figure 4: 3D Model shown the main faults crosses the wells.

4. GEOPHYSICS

The micro-seismic results of the injection well SP03 had earthquakes with an average of 1.3° in magnitude of coda at depths of 2.5 km. The focal mechanisms of these earthquakes, that is the orientations of the structures in which the earthquakes are occurring, correspond to faults with orientations predominantly Northeast-Southeast and North-South.

The gravimetric results were used on the residual Bouguer anomaly data with Gauss filter in order to identify slim structures. Two wide range anomalies can be seen in Gauss filter; these anomalies might delineate the underground structure of the area as a possible response for elevated crystalline blocks that comprise the basements.

The magneto-telluric shows two zones of discontinuity in the resistivity were identified. The first one with N-S orientation east of the San Pedro Dome and the second with slightly E-W orientation to the north and central sector of the Domes of San Pedro.

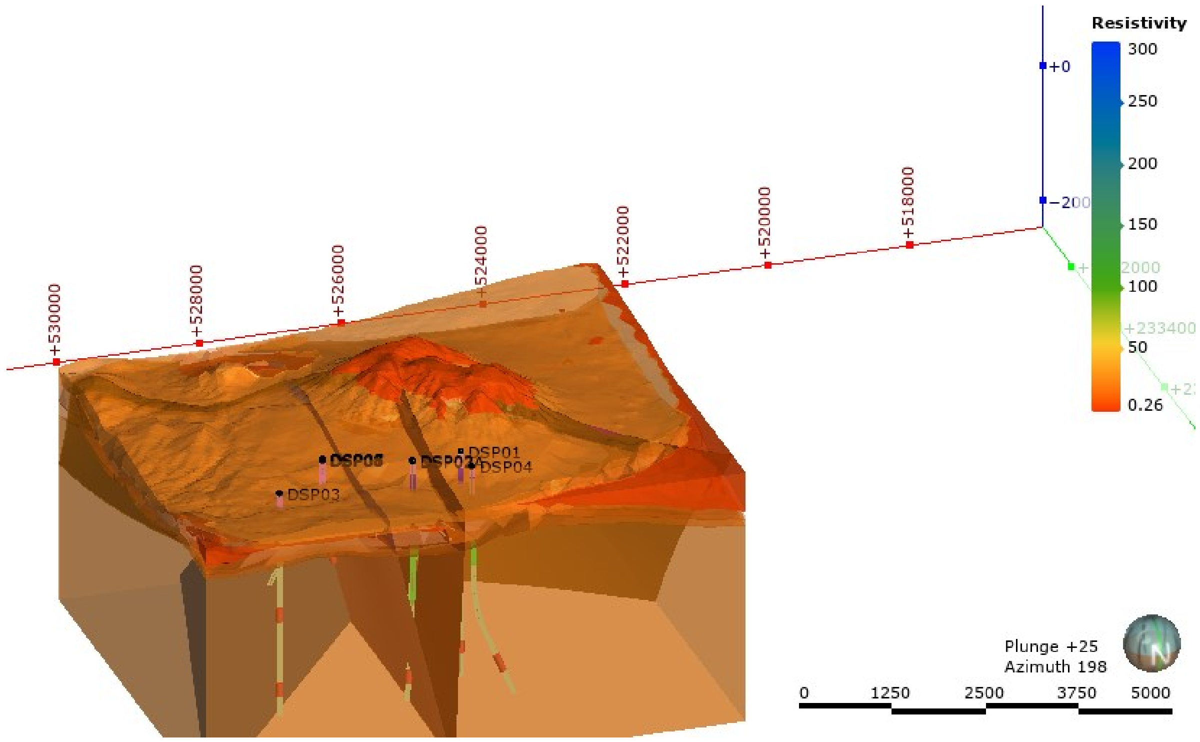

Figure 5: 3D Model shown the resistivity and N-S faults related with the discontinuity.

5. APPLICATION

The scope in application of a 3D model is wide, allowing to continue expanding the geothermal field by planning an exploration well until analyzing the operation of existing wells. An example of this is the case of a producing well that decreased its production. This well was drilled in December 2013 with a total depth of 3754 m MD. In March 2016, the began to grow its steam production, from an initial average of 25.2 t/h in April 2016, to a maximum of 47.6 t/h in October of the same year and subsequently decreasing its production capacity at an average rate of 0.023 t/h of steam per day and the enthalpy showed a constant upward trend.

The alteration zones of the well could be analyzed, and this is related to andesitic and rhyolitic dykes. This well presented a peculiarity since the permeability zones had platy calcite. Also, a speciation simulation was performed using a geochemical speciation program shown a oversaturation with respect to calcite and silica. Whereas the calcite oversaturation content of the brine is a consequence of high bicarbonates, calcium and pH. This allowed calcite deposition in the flash zone.

Finally, on March 2019, the well decreased to 7 t/h of steam and 9.3 bar wellhead pressure and due to fully integrate to the steam management system the well was shut-in.

As shown in Table 1, a chemical stimulation was executed in July 2019 with 3 main stages for the workover. The workover began with the pumping of 206.9 m3 of HCl 10% and finished with alkaline stage.

Table 1: Chemical stimulation plan to production well

Stage	Fluid type	Volume (m3)	Flow rate (m3/h)	Method
1	HCl 10%	206.9	48	Bullheading
2	HCl 10% + Formic Acid 4%	86.3	48	Bullheading
4	Alkaline Solution	98.8	17	Coiled Tubing Unit

The results of chemical stimulation after integration of the well to shown in Table 2 where the steam supply difference after the workover is 18.6 t/h, roughly equivalent to 2.6 MW, and an improvement of 351%. The brine flow increase is considerably larger, but that is because, at the time this writing was submitted, the well was still discharging the fluids used in the workover. The wellhead pressure increase is close to 2.5 barg.

Table 2: Results after of chemical stimulation

Parameter	Before Shut-in	After acid workover
Steam Flow (t/h)	7.4	26.0
Brine Flow (t/h)	14.8	60.3
Wellhead Pressure (barg)	9.36	11.4
Permeability (md)	0.2	N/A
Skin	-3.2	N/A

ACKNOWLEDGEMENTS

The authors would like to thank the Grupo Dragon for the permission in publishing this paper.

REFERENCES

DeMets, C., Stein, S. (1990): Present-day kinematics of the Rivera plate and implications for tectonics in southwestern Mexico. *Journal of Geophysics Research* 95 (B13), 21931-21948.

DeMets, C., Traylen, S.: Motion of the Rivera plate since 10 Ma relative to the Pacific and North American plates and the mantle. *Tectonophysics*, 318, (2000), 407-415.

Diaz-Bravo, B.A. et al. (2014): The origin of intraplate magmatism in the western Trans-Mexican Volcanic Belt. *Geosphere*, v. 10, num. 2, 340-373.

Ferrari, L., et al.: Regional tectonics of western Mexico and its implications for the northern boundary of the Jalisco Block. *Geofisica Internacional*, Vol. 33, num. 1, (1994), 139-151.

Ferrari, L., et al. (1999): Geology of the western Mexican Volcanoc Belt and adjacent Sierra Madre Occidental and Jalisco Block. *Geological Society of America*, special Paper, 334.

Ferrari, L., Rosas-Elguera, J. (2000): Late Miocene to Quaternary extensión at the northern boundary of the Jalisco block, western Mexico: the Tepic-Zacoalco Rift revised, in Degalgo-Granados, H., Aguirre-Diaz, G., Stock, J.M. (eds.), Cenozoic Tectonics and Volcanism of Mexico: Bouder, *Geological Society of America*, Special Paper, 334, 41-64.

Ferrari, L., et al. (2000): Geology of the western Mexican Volcanic Belt and adjacent Sierra Madre Occidental and Jalisco Block, in Degalgo-Granados, H., Aguirre-Diaz, G., Stock, J.M. (eds.), Cenozoic Tectonics and Volcanism of Mexico: Bouder, *Geological Society of America*, Special Paper, 334, 65-84.

Ferrari, L., et al. (2002): Ignimbrite flare up and deformation in the southern Sierra Madre Occidental, western Mexico: implications for the late subduction history of the Farallon plate. Tectonics, 21(4), 17, 1/24.

Ferrari, L., et al. (2003): Geology of the San Pedro – Ceboruco Graben, western Trans-Mexican Volcanic Belt. *Revista Mexicana de Ciencias Geologicas,* v. 20, num. 3, 165-181.

Frey, H.M. et al. (2004): Magma eruption rate constrained by 40Ar-39Ar chronology and GIS for the Ceboruco-san Pedro volcanic field, western Mexico. *Geological Society of America Bulletin*, v. 166, 259-276.

Frey, H.M., et al. (2007): A Pliocene ignimbrite flare-up along the Tepic-Zacoalco rift: evidence for the initial stages of rifting between the Jalisco Block (Mexico) and the North America. *Geological Society of America, Bull*. 199 (1-2), 49-64.

GEOTEM. (2017): Estudio Geofísico en el Domo de San Pedro y sus alrededores, Municipio de San Pedro Lagunillas, Nayarit, Mexico. Internal Report for Grupo Dragon. *GEOTEM Ingeniería S.A. de C.V.*

Petrone, C.M., et al. (2001): Volcanic systems in the San Pedro-Ceboruco graben (Nayarit, Mexico) in the light of new K-Ar geochronological data. *Geochemical Journal*, Vol. 35, 77-88.

Petrone, C.M. et al. (2006): The San Pedro – Cerro Grande volcanic complex (Nayarit, Mexico): Inference on volcanology and magma evolution. *Geological Society of America*, special Paper 402, 62-97.

West Jec. (2017): DSP Final Report for GD. Internal Report for Grupo Dragon. *West Jec Japan Engineering Consultants, Inc*.