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The Conceptual Model and its Evolution over 15 Years of Development and Operation: San Jacinto-Tizate Geothermal Field, Nicaragua

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ABSTRACT

Exploration began at the San Jacinto – Tizate geothermal system in the early 1950s and the field has been under production since 2005. Early exploration was undertaken by several different organisations until the geothermal concession was acquired by Polaris Energy Nicaragua S.A. (PENSA) in 2003. Jacobs has continued working as technical advisor since becoming involved in the project in 1999. Since the early days of exploration, the conceptual model has evolved considerably, from a relatively simple one, based on limited initial data, to a more thorough and nuanced model that has recently been updated annually. The model continues to be refined as new data is acquired through ongoing production and field management activities, and with the incorporation of results of makeup drilling and geoscientific work.

The geothermal system is centred in a step-over along a NNE striking regional structure that results in N-S structural grain within the field with a component of E-W extension. The resource is recharged by a high temperature (>300°C) neutral chloride water with a salinity of about 5,500 ppm and a gas content of 0.25-0.30 wt%. This rises from depth along the eastern central margin of the production field and spreads to the west, north, and south. The field is bounded by low permeability zones to the north, east, and west, and historically outflowed to the South toward the village of San Jacinto. This has resulted in a NNE-SSW elongation of the system that is evident in the most recent MT geophysics survey. Additionally, there is a second, seemingly unconnected but potentially larger, geothermal system ~5 km to the west of the currently operating project.

Since the field has come under increased production in 2012, when the installed capacity was expanded in two stages to 72 MWe, the historic outflow to the south has reversed due to pressure drawdown in the reservoir, causing the still hot outflow fluids to be pulled back towards the reservoir. The effects of pressure drawdown have resulted in the development of a steam cap in the central production area, which has created both challenges and opportunities in the ongoing management of the reservoir. Despite these changes in resource characteristics the field is performing well and the project operating close to its total installed generation capacity.

While the conceptual model has been extensively tested and refined over the years, some uncertainties remain. The nature of structural controls within the production field have evolved from numerous discrete faults to considering more distributed fracturing as in a horsetail fault swarm. Our understanding of the structural controls in the very deep levels of the field and how they cause the westward trending rise of the geothermal fluids from depth are still being refined. The degree of connection between the northern lobe of the field and the central production field is currently being investigated.

1. INTRODUCTION

The San Jacinto-Tizate geothermal system is located in northwestern Nicaragua on the eastern side of the Telica volcanic complex approximately 20 km north of the city of Leon (Figure 1). The project commenced geothermal power production in 2005 and remains the largest renewable energy project in Nicaragua. The total installed generation capacity of 77 MWe (gross) represents approximately 10% of the total power capacity of Nicaragua. The project is operated by Polaris Energy Nicaragua S.A, a subsidiary of Polaris Infrastructure, which is listed on the Toronto Stock Exchange. San Jacinto is the second geothermal project to be developed in Nicaragua following earlier development at Momotombo located approximately 50 km to the southeast.

2. DEVELOPMENT HISTORY OF SAN JACINTO

The history of key drilling campaigns and plant commissioning events performed at San Jacinto is summarised in Table 1. The first exploration studies at San Jacinto were undertaken in 1953 by McBirney (McBirney and Williams, 1965). These included the drilling of three shallow investigation holes to a maximum depth of 86 m, with the final hole producing steam from a fracture encountered at 60 m.

The first major exploration of the resource began in 1993 with a Nicaraguan-Russian company, Intergeoterm. The initial phase of exploration drilling concluded in 1995 with the completion of 6 deep wells and the partial drilling of a 7th, and confirmed the presence of a relatively low gas (<0.4 wt %) liquid-dominated neutral chloride resource, with a temperature range of 260°C – 300°C in the central upflow area. In 2003 the project was acquired by Polaris Energy Nicaragua S.A., who was assisted by SKM (later acquired by Jacobs) in evaluating the resource potential and in developing and implementing a strategy for the commercial development of the resource. A 10 MWe back pressure plant was commissioned in 2005.

Figure 1: San Jacinto project location and the major volcanic complexes of northern Nicaragua

Following the acquisition of Polaris by Ram Power in 2009, a drilling program was initiated by Ram Power in 2010 to increase the project generation capacity to 72 MWe net using 2 x 36 MWe Fuji Electric steam condensing turbines, to replace the existing 10 MWe back pressure plant. The new turbines were successfully commissioned in January and December 2012, respectively. Since 2012 there have been three further drilling campaigns to provide make-up steam production and to improve the performance of some the injection wells. These campaigns included a combination of new wells (infield and step out), some with multilateral completions, supplemented by acid stimulation programs to enhance injection well capacity.

Table 1: Key drilling campaigns and plant commissioning events (highlighted in blue) at San Jacinto

Year(s)	Activity
1953	Initial exploration work undertaken by McBirney, including the drilling of 3 wells up to 86 m deep.
1969-1971	Drilling of four temperature gradient wells through the US Aid program.
1993-1995	Exploration drilling by Intergeoterm (SJ1-1, SJ2-1, SJ3-1, SJ4-1, SJ5-1, SJ6-1, SJ7-1).
2005	Commissioning of 2 x 5 MWe backpressure units (Units 1 and 2) in July 2005.
2007-2008	2^{nd} drilling campaign (SJ6-2, SJ8-1, SJ9-1, SJ9-2, SJ9-2 ST1, SJ10-1).
2010-2011	3^{rd} drilling campaign (SJ9-2 ST2, SJ9-2 ST3, SJ9-3, SJ11-1, SJ11-1 F1, SJ12-1, SJ12-1 ST1, SJ12-2, SJ12-2 F1, SJ12-3).
2012	Commissioning of 2 x 36 MWe steam condensing units (Units 3 and 4) in January and December 2012.
2013	4^{th} drilling campaign (SJ9-3 F1, SJ12-3 F1. Well workover and stimulation).
2015-2016	5^{th} drilling campaign (SJ6-3, SJ9-4, SJ14-1, SJ14-1 ST1, SJ14-1 ST2).
2017	6^{th} drilling campaign (SJ4-2, SJ11-2, SJ12-4, and SJ12-5).

Abbreviations: F = forked/multi-lateral well, ST = side tracked well

The project has a very high level of utilization of the wells that have been drilled, with only 3 early wells having been plugged and abandoned, and with only 1 idle well (SJ14-1) (occasionally used for Condensate injection) after the SJ3-1 monitoring well was recently successfully put on to production. There are presently 15 production wells in service, and 7 used for brine or condensate injection. A total of 4 wells (3 producers and 1 injector), were successfully completed with a multi-lateral (forked) construction to enhance their capacities (Figure 3).

3. GEOLOGY AND STRUCTURAL SETTING

3.1. Regional Geological Setting

Nicaragua is situated on the southern portion of the Chortis block, a sub-block of the Caribbean plate. The Cocos Plate subducts beneath the Caribbean and North American plates, at a rate that is among the fastest in the world (8 cm/yr; Weinberg, 1992). Subduction of the Cocos Plate beneath the Caribbean Plate has produced a chain of calc-alkaline stratovolcanoes, calderas, and monogenetic volcanic features such as domes, cinder cones, maars, and tuff rings that constitute the Los Marrabios Mountain Chain in Nicaragua. These volcanic features are situated along the southwestern margin of the northwest-trending Nicaraguan Depression (Figure 2)), which is interpreted as a half-graben with steeply-dipping bounding faults to the southwest (Funk et al., 2009). High temperature geothermal systems in Nicaragua are generally associated with shallow crustal heat sources along this magmatic front.

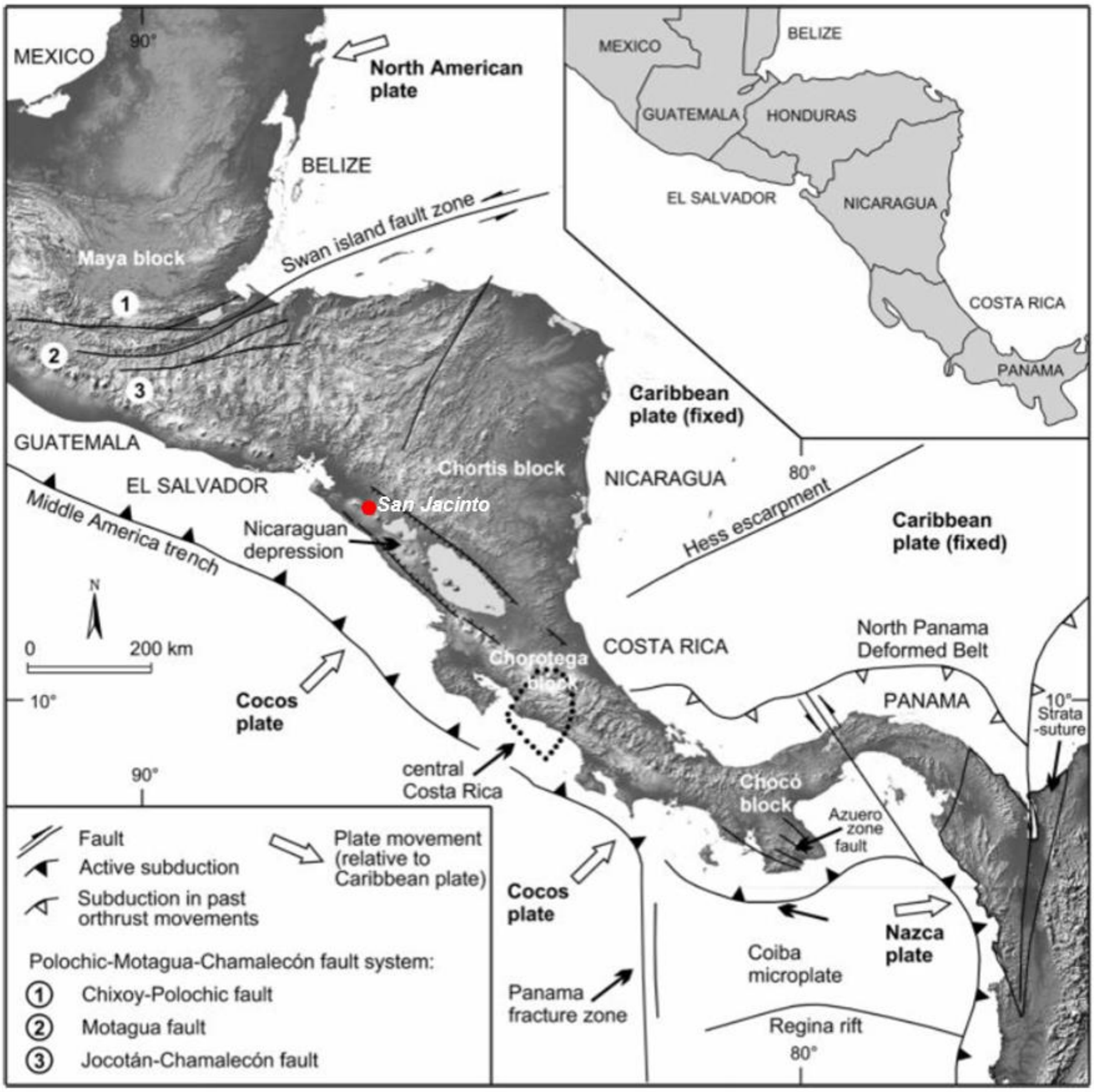

Figure 2: Tectonic map of Central America showing the location of the San Jacinto geothermal field (Bundschuh et al., 2007).

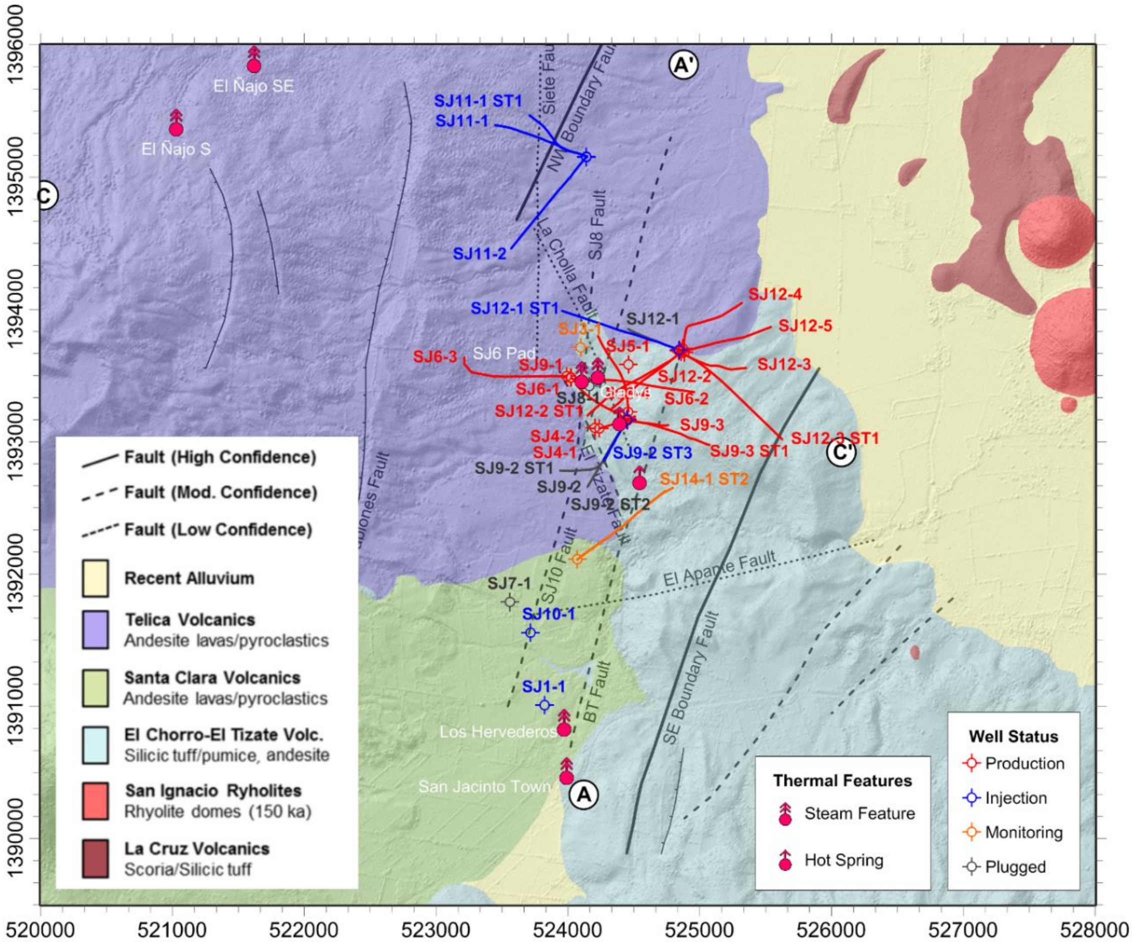

Figure 3: San Jacinto well location map, surface geology, primary geological structures, and surface thermal manifestations

3.2. Local Geology and Structure

The San Jacinto-El Tizate concession is located a few kilometres to the east of the Telica volcanic complex, which is part of the Los Marrabios volcanic chain. Telica has erupted frequently since the beginning of the Spanish era and most recently in May 2016. Superheated (350°C), SO_2-rich fumaroles are found in the central crater of Telica (Smithsonian, 1999). Telica is the most western part of a west-east trending volcanic complex with numerous volcanic centres, each with an apparent increase in age towards the east.

The youngest volcanism northeast of El Tizate appears to be the San Ignacio (Dom Bosco) Domes that lie in the lower elevation plains about 3 km east of the geothermal field. They have a youthful appearance and lie within nested tuff rings. There is a third tuff ring to the east that lacks a central dome, and remnants of older ones to the northwest. GeothermEx (2001) gives an age of 150,000 years for the domes, based on thermo-luminescence, which is a more likely age than the 480 ka K/Ar date reported in OLADE (1981).

Geological mapping efforts at San Jacinto have been summarized by White (2008), Rohrs et al. (2014), and Norini (2016). The surface geology of the area is primarily composed of andesitic lavas and pyroclastics, and silicic tuff/pumice related to the volcanic centres discussed above (Figure 3). An extensive area previously mapped as diorite intrusive outcropping southeast of the easternmost production wells has recently been reclassified as highly porphyritic andesitic lava. This interpretation is consistent with the paucity of intrusives found in nearly all wells drilled to date.

Norini (2016) made structural measurements on outcrops in and around the San Jacinto geothermal field, however it was noted that geological outcrops are scarce in the region due to the thick vegetation and soil cover. Mapped faults mainly offset pyroclastic deposits, debris flow deposits, and lava flows of Quaternary age, and are commonly hydrothermally altered. While the various mapping studies have provided many inconsistencies in interpretation, the joint consideration of surface study information, the regional tectonic setting, and structural features identified in the reservoir by drilling enables some specific fault structures to be more confidently identified over other postulated features (Figure 3).

4. SURFACE THERMAL ACTIVITY

Surface thermal activity at San Jacinto is primarily characterised by extensive areas of steam-heated activity at several locations at San Jacinto including San Jacinto town to the south of the project, nearby Los Hervederos and several areas within the central production area. The activity consists mainly of steam vents and mud pools in San Jacinto town, with fumarolic activity and large areas of diffusively steaming ground being more prevalent in the central production area.

The steaming ground is a result of boiling in the upper 500 m of the geothermal system, with most wells having temperature profiles that lie on or close to the boiling-point-for-depth curve. The major steam emissions near the SJ6 pad (Gladys and SJ6 fumaroles) and SJ5 pad were monitored regularly between 2005 and 2011 and had gas contents in the range of 1-3 wt%. Both showed a steady increase in gas content and intensity in the two-year period after the commissioning of the initial 10 MWe pilot plant, probably resulting from expansion of boiling in the shallow reservoir. The steam-heated features at San Jacinto town and nearby Los Hervederos have a much lower and steady gas content of about 0.3 wt%, consistent with steam derived from an already boiled, partly degassed outflow from the north.

A hot seep located about 430 m south of SJ4-1 and sampled in 2001 (prior to the initial 10 MWe power plant commissioning) had a high chloride concentration (1,650 ppm), confirming that deep reservoir water reached the surface. More recent data is not available as pressure drawdown in the reservoir and an evolving shallow steam zone has caused the seep to cease flowing.

Since late 2017 there has been a notable increase in surface steam flow activity in the central production area which is attributable to the development of a steam zone in response to pressure drawdown and boiling in the deep reservoir. Surface activity comprising mainly steaming ground with some mud pots has increased in both extent and intensity, with activity being notably more vigorous following periods of rain due to the boiling-off of rainwater that is either ponded on the surface or contained with perched aquifers in the shallow subsurface.

There are two additional fumarole features at El Najo some 4 km NE of the present development (Figure 3). These are the north-easterly most manifestations associated with a potentially larger, but as yet undrilled, geothermal resource referred to as the San Jacinto West Sector.

5. WELLFIELD INFORMATION

Nearly 15 years of well operation history coupled with a comprehensive reservoir monitoring program has enabled a good understanding of well behaviour trends to be determined along with changes in broader reservoir characteristics.

5.1. Temperature Distribution

The temperature in the system in 'Natural State' before production is presented in Figure 4.

5.2. Production and Injection Scheme and Performance

Production started in 2005 feeding the 2 x 5 MWe back pressure power plant which were replaced in 2012 by more efficient condensing steam turbine units. The total mass produced from the field has been increased following the construction of these units and in line with make up well drilling programs. Figure 5 shows the total mass extraction from the field over time, the total injection loads, and the timing of key plant commissioning events.

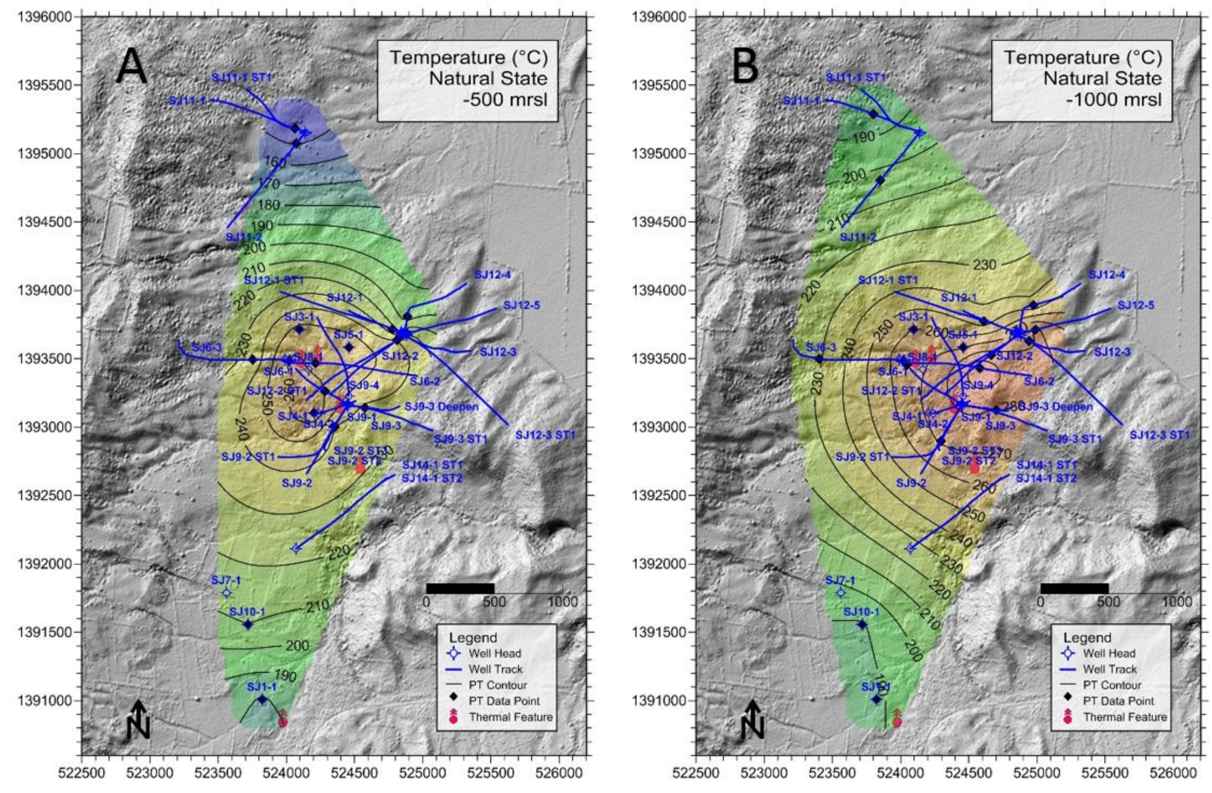

Figure 4: Natural state temperature distribution at (A) -500 and (B) -1,000 mrsl

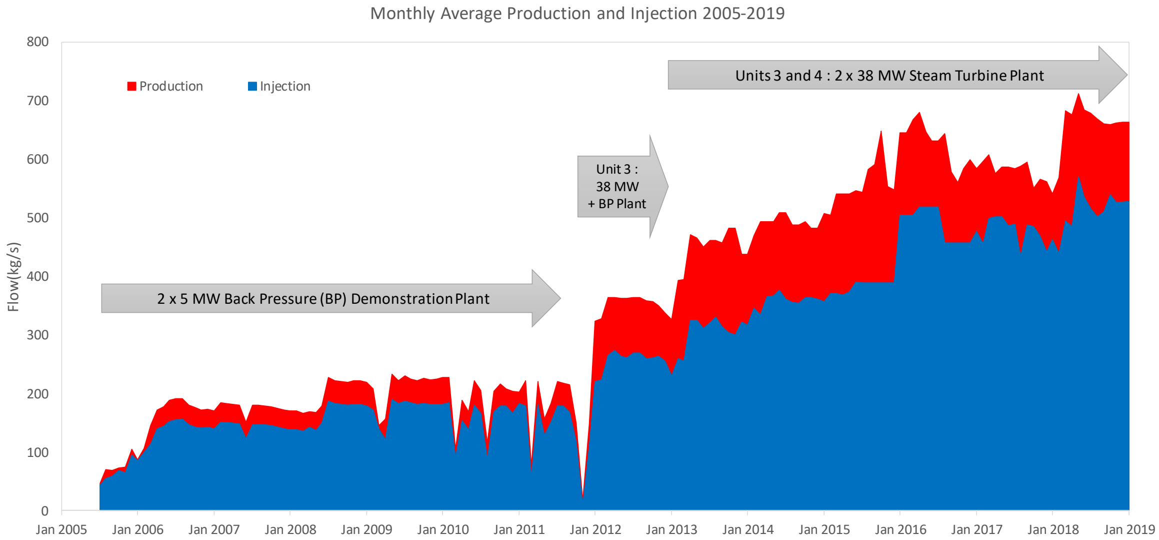

Figure 5: Total production from field (mass flow) from July 2005 to January 2019

The location of production and injection in 2019 is shown in Figure 6. Production is taken from the central high temperature reservoir at a range of depths and injected mostly in the wells SJ11-2 in the north and SJ10-1 and SJ1-1 in the south, with minor in-field injection of brine and condensate in SJ9-2 and SJ12-1.

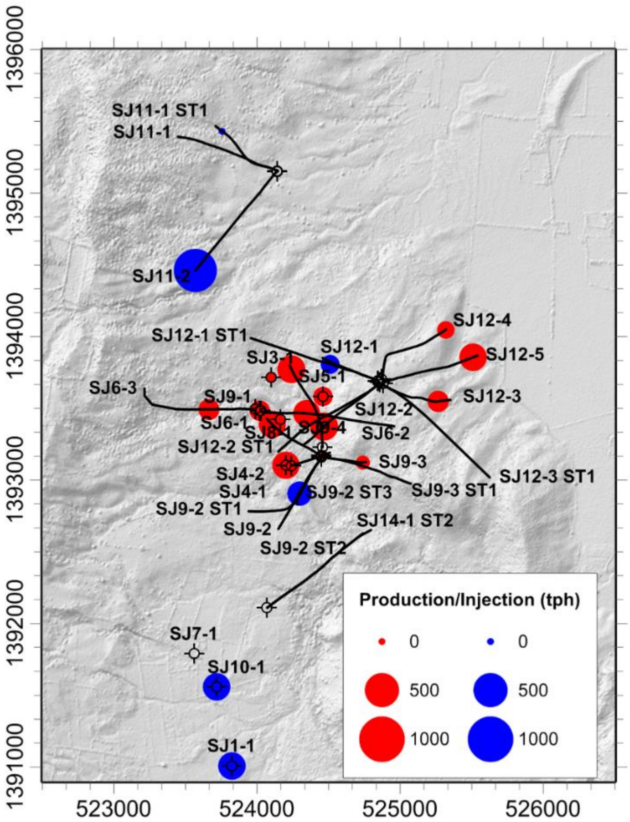

Figure 6: Average weekly flow (tph) for production and injection wells at San Jacinto in July 2019. For simplicity, mass flow is allocated to the major feed or permeable location for each well

6. INTEGRATED CONCEPTUAL MODEL

The key elements that comprise the integrated San Jacinto conceptual model are summarised in Table 2, including the main data sources that have been used for interpretation and the level of confidence of conceptual understanding based on a review of those data.

Table 2: Key elements of the San Jacinto Conceptual Model

Parameter	Hypothesis	Confidence	Available Data Sources
Reservoir Temperature/Hydrology	Deep upflow of 310°C+ fluid, rising from the east (SJ12-3) and ascending on an angled path towards the western part of the production field (SJ4-1). Natural state outflow primarily directed to the south.	High	Downhole T measurements Fluid chemistry Alteration mineralogy
Reservoir Chemistry	The deep, pre-boiled reservoir water has a neutral pH, sodium-chloride composition with salinity of about 5,500 ppm, and a gas content of 0.25 – 0.30 wt%. The shallow reservoir is boiled, cooled and degassed and locally affected by injectate returns. Groundwater incursion is minimal.	High	Fluid chemistry Alteration mineralogy
Permeability Controls and Structural Context	Hybrid structural setting involving a horsetail splay and extensional step-over (or bend) of a regional-scale sinistral fault. The production field is entirely situated in the step-over region between the two bounding sinistral faults. The dominant permeability control is secondary features (faults and fractures). The primary fracture grain is ~N-S.	Moderate-High	FMI and Acoustic imaging logs Downhole PTS measurements Surface mapping and analysis of regional tectonic setting Tracer injection testing
Reservoir Area/Boundaries	The primary reservoir area, where proven temperatures >250°C can found at -1,000 mrsl is at least 2 km^2. Thick conductor to the east of the field serves as an eastern margin. The deep high resistivity body associated with reservoir is elongated ~N-S, parallel to a prominent regional structural trend. There is a possible northern extension of the deep reservoir.	Moderate-High	MT resistivity Downhole PTS measurements
Host Lithologies	Andesite lavas and pyroclastics with lesser occurrences of diorite and basalt. Subordinate/discontinuous sedimentary units.	High	Geological mapping and well logs FMI and acoustic logs
Heat Source	Heat source to the east of the field. The San Ignacio domes represent youngest volcanic activity in the east possibly from a cooling magma that is the present heat source.	Moderate	Fluid chemistry Downhole T measurements MT Resistivity Radiometric age dating
Production-Induced Effects	Steam Zone Development Field-wide pressure decline has led to the development of a steam zone above the central upflow path. The interconnectivity of this zone remains uncertain and is likely to be continuing to evolve.	Moderate	Downhole PT measurements and long-term trend analysis Well production data Microgravity InSAR Increased surface activity
Temperature/ Hydrology Trends	Marginal fluids and degassed outflow fluids are likely being drawn into the production area as a result of the pressure drawdown, resulting in a temperature decline in the shallow reservoir. Whereas the upper reservoir has been affected by temperature decline, the deep reservoir temperature has remained fairly constant throughout the production history of the field.	High	Downhole PT measurements Fluid chemistry
Pressure Trends	Field wide pressure drawdown from natural state conditions, including in injection regions. There is a pressure disconnect between deep and shallow permeable zones in some wells.	High	Downhole P trends
Chemistry Trends	Increasing Cl contents of production fluids from wells with shallow feeds in coincidence with declining shallow reservoir temperatures indicative of influx of marginal (boiled) fluids into system.	High	Fluid Chemistry

Abbreviations: FMI = formation micro-imaging, MT = magneto-telluric, P,T,S = pressure, temperature, spinner, InSAR = interferometric synthetic aperture radar

The function of a resource conceptual model is to develop a holistic understanding of the system in question that satisfies the observable data. The model, including potential alternative interpretations, is a live tool that is progressively updated over the project lifecycle as new field monitoring information and any new drilling and well performance testing is done.

The datasets outlined in Table 2 have been jointly assessed to develop an updated conceptual model for the San Jacinto geothermal field. The culmination of this effort has shed new light on some resource parameters that are discussed the sections below and which are illustrated in the N-S (Figure 7) and NW-SE (Figure 8) oriented conceptual model cross-sections. How the system has changed under production also adds considerable information regarding the hydrodynamics and processes occurring in the hydrothermal system.

6.1. Reservoir Temperatures, Pressures and Hydrology

The hottest wells (>310°C) are found located on the eastern side of the field and indicate that the deep upflow is situated on the eastern side of the system. The upflow rises along a westward-directed path, rising to an apex below the region of the SJ4 and SJ9 pads. The geometry of this pathway appears to be controlled by a deep low resistivity body in the east, representing a low permeability eastern margin to the system that deflects the upflow westwards as it rises. Upflow is enabled along the N-S fracturing that transects the field here. Temperatures generally follow a boiling point with depth curve in the upper 600 m of the system.

Interpreted temperatures below an elevation of -800 mrsl (~1,000 mVD) are >250°C for all wells in the main production field, apart from SJ6-3 which was drilled into the western margin of the system. Shallow feed zones that occur between elevations of -300 and -800 mrsl in the main production field are all ≥220°C. Some of these shallow feeds are interpreted to represent vapour-mobile two-phase regions (steam zones). Some steam zones may have been present before production started but they have substantially developed and/or grew in response to the production-induced reservoir pressure drawdown, particularly following the large increase in field production following the commissioning of Units 3 and 4 in 2012.

A prominent temperature reversal in SJ6-3, and deeper reversals in SJ3-1 and SJ6-1 provide an indication of outflow to the west and north-western regions of the main production field, respectively. Shallow temperature reversals in the southern injection wells reflect the prominent southward outflow that extends from the production area and feeds the manifestations at Los Hervederos and the San Jacinto town.

6.2. Reservoir Chemistry

The deep upflow at San Jacinto is a >310°C, single-phase, liquid water with a neutral pH, sodium chloride composition, salinity of about 5,500 ppm and low dissolved gas content of 0.25-0.30 wt%. Some wells also produce from deep levels and high temperatures (>280°C) and are slightly diluted and/or boiled with respect to the inferred upflow water.

The deep reservoir water upflows and recharges a shallow aquifer at 500-1,000 m produced by SJ4-1, 9-1 and 6-2. In the natural state this water reached the surface as chloride-rich seeps previously reported near SJ4-1 while shallow boiling produced steam-generated activity near SJ1-1 and between SJ4-1 and SJ5-1. At shallow depths the water outflowed to marginal cooler aquifers at the edges of the reservoir.

With ongoing production and pressure decline the primary processes controlling chemistry in the shallow parts of the reservoir are boiling and returns of injectate from the south. Both have caused, cooling, degassing of reservoir brine (gas contents of <0.02 wt% in liquid-feeding wells) and increasing salinity. This clearly evident from the pronounced chloride-enthalpy trend of the reservoir water. There is very little evidence for significant incursion of shallow unmineralized groundwater.

Most wells continue to produce with close to single-phase liquid enthalpies, however several wells show the increased enthalpy associated with the presence of steam, which is also characterised by increases in gas content.

6.3. Permeability Controls and Structural Context

At a regional scale, the San Jacinto geothermal field can be explained in the context of a hybrid structural setting involving a horsetail splay and a left extensional step (bend?) of a 10+ km-long left-lateral fault (the SE Boundary Fault). Elevated strain that occurs at this zone of structural complexity facilitates the generation and stimulation of fractures, providing permeability to accommodate the geothermal system.

Permeability in the system is dominantly controlled by secondary features such as fractures and faults. There are some indications from geological mapping and the alignment of permeable zones and thermal manifestations that some discrete N-NNE striking and NW striking structures may represent quasi-planar permeability targets. However, a significant amount of permeability in the system is not easily relatable to field-wide planar structures, and data from FMI logs suggest that these are likely to be either zones of highly fractured andesites, permeable contacts between flow/volcaniclastic units, and smaller-scale shear fractures (faults) that may be subsidiary to some of the mapped larger-scale structures. Downhole FMI and acoustic imaging logs run within the productive reservoir confirm that there is strong and widely distributed open fracturing predominantly striking between NNE-SSW and NNW-SSE, which is generally consistent with other permeability control indicators including the regional tectonic setting. This has driven a philosophy of targeting wells in a generally E-W direction and which has mostly proven successful intercepting permeability associated with this prevailing grain of open fracturing.

6.4. Host Rocks

The dominant lithologies intersected in San Jacinto wells are intercalated andesitic lavas and breccias, crystal/lithic tuffs, and basaltic lava and scoria. A massive intrusive diorite body was also intersected in the bottom 600 m of SJ7-1 and minor diorite dykes have been intersected elsewhere in the field. Minor volcaniclastic sedimentary lenses have been intersected in the upper 200 m of SJ10-1. These sedimentary lenses are comprised of tuffaceous sandstones and siltstones, which were likely deposited in local paleo-fluvial and paleo-lacustrine environments. Rare microfossils have been observed in some thin sections and it is possible that some of the units that were mapped as tuff in other wells are in fact epiclastic tuffaceous sediments, particularly in units where clasts are documented as rounded.

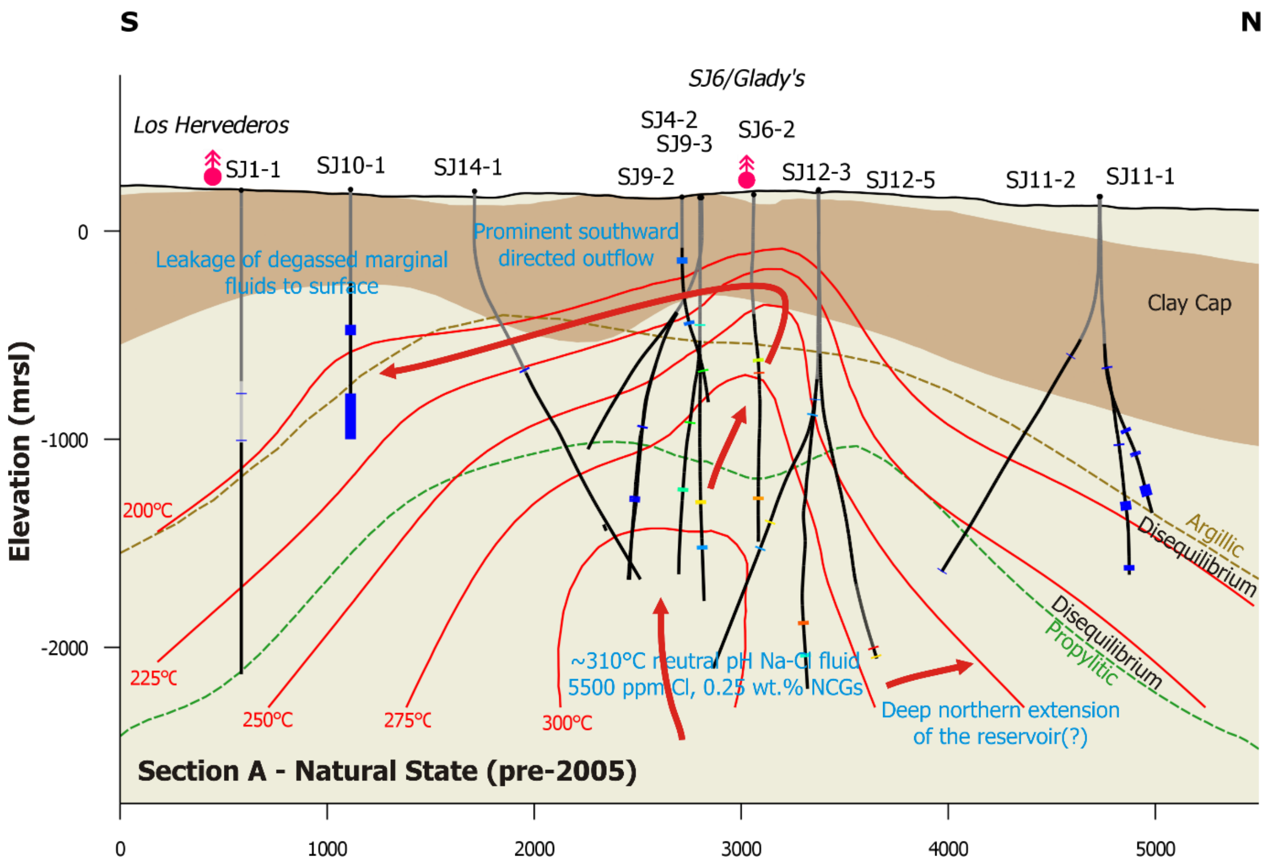

Figure 7. N-S cross section (A-A'; Figure 3) through the natural state conceptual model for San Jacinto

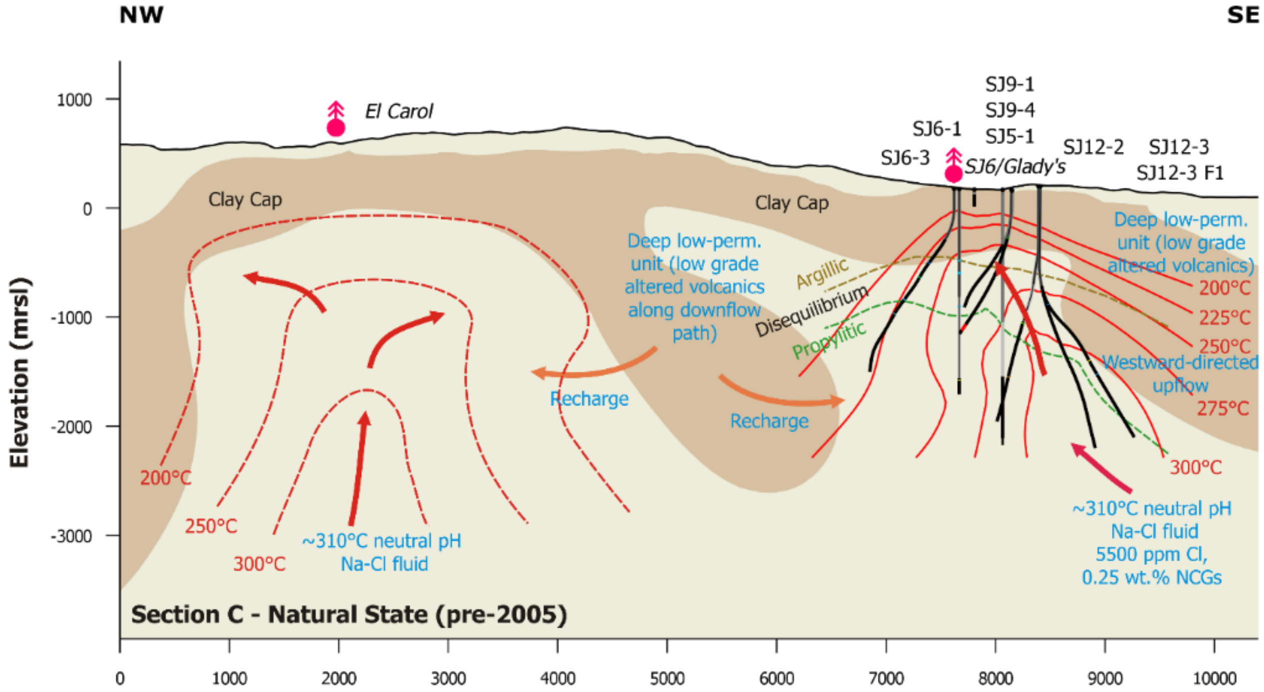

Figure 8. NE-SW cross section (C-C'; Figure 3) through the natural state conceptual model for San Jacinto and the Western Sector

It is currently not possible to confidently subdivide the subsurface stratigraphy at San Jacinto into mappable sub-units as a result of the relatively uniform composition and laterally discontinuous nature of units that form the volcanic pile. No regional basement rocks or regional-scale plutonic bodies have been encountered in any wells drilled in the field.

6.5. Resource Area and Volume

The eastern margin of the field is represented by a thick, steeply-dipping low resistivity body that is aligned NNE, parallel with the regional structural grain and the northward extension of the SE Boundary Fault. The bottom few hundred meters of SJ12-3 F1, which was characterized by low permeability conditions, appears to have been drilled into this margin. The western margin of the field is primarily defined by a steep declining temperature gradient and deep temperature inversion that was measured in SJ6-3. A significant permeability barrier occurs just to the east of SJ6-1 and SJ3-1. This separates these western wells from those in the east that have highest pressure drawdown in the reservoir, and appears important in the system response to production but was not evident as a barrier in the natural state temperature and pressure patterns. The southern margin of the production field has mixed characteristics; some of the SJ9-2 legs showing low permeability at depth, but SJ14-1 found some deep permeability before that part of the well was lost. There was a clear outflow to the south in the natural state, probably at intermediate and shallow depths, and the pressure response in SJ1-1 and SJ10-1 to central production indicates that a wide area to the south is connected to the production field. The northern extent of the system remains somewhat ambiguous, as there are indications provided by the resistivity patterns and temperature heat-up surveys indicate in SJ11-2 that deep >~240°C conditions may extend as far as 1 km north of the main drilled production field.

The deep high resistivity body generally associated with the production reservoir is elongated in a NNE orientation, parallel to the regional structural trend and this may explain why the reservoir at SJ11-1 was apparently already drawn down when this well was drilled. This northern extension is bounded to the east and west by deep low resistivity bodies, the former which was penetrated by SJ11-1.

The currently defined area where >250°C fluid is present at -1,000 mrsl in the San Jacinto field is ~2 km^2.

The thickness of the reservoir is uncertain. The predominantly andesitic stratigraphy is present throughout the entire extent of all drilled wells, some which reach elevations down to -2,200 mrsl (~2,400 mVD). There is thus no discernible basement lithology to assist with characterizing a lower boundary. There are some indications that deep regions bearing temperatures >300°C have poor permeability characteristics, as was found to be the case in some easternmost wells drilled close to the inferred system upflow. Western wells with deep temperature inversions indicate that base of useful reservoir may be defined by temperature rather than permeability limitations. Following this logic, the base of the reservoir throughout the main production area may extend to vertical depths of 2,000 - 2,500 m. If a slightly cooler northern extension of the reservoir exists, the lower boundary may extend deeper than this, but perhaps to depths that become impractical or uneconomic to target with conventional drilling methods.

The extent of the prospective Western Sector remains untested by drilling, however the resistivity signature and characteristics of surface manifestations suggest a likely high temperature (>250°C) reservoir area of 3-5 km^2 or more. A NE-striking low-resistivity body separates the Western Sector from the northern region of the San Jacinto field.

6.6. Heat Source

The nature of reservoir isotherm geometry and the prominent inversions in temperature profiles (outflow indications) to the south and west, suggests that the heat source for the system is situated to the east of the field. It is potentially related to a shallow crustal magmatic body that produced the Pleistocene San Ignacio domes or the recently proposed El Chorro volcano (Norini, 2018).

There is a deep conductive (likely low-permeability) body that exists to the west of the San Jacinto field (intersected by the deep parts of SJ11-1) that separates the geothermal system at San Jacinto from the Western Sector and the thermal manifestations at El Carol and El Najo. Data from the 3D MT inversion model, the interpreted isotherms for San Jacinto, the distribution of thermal manifestations, and the surface volcanology/geology all suggest that the heat source for the Western Sector of the system is separate from that which fuels the San Jacinto field, and is more likely related to the active magmatic heat source beneath the Telica volcanic complex.

6.7. Pre-Production System Evolution

The presence of a mixed argillic-propylitic disequilibrium alteration mineral zone in most wells at San Jacinto is an indication of spatially and temporally evolving thermal conditions in the system. The distribution of this zone provides an indication that southern, northern, and western parts of the system were once subject to temperatures hotter than the estimated natural state (pre-production) isotherms. Conversely, the distribution of this zone relative to the interpreted natural state isotherms provides an indication that the central and eastern parts of the system are undergoing a heating trend. The timescales associated with the pre-production changes are unknown, however, they have likely occurred over periods of centuries to millennia.

Localized occurrences of high grade propylitic and hornfelsic alteration associated with dyke intrusion events are also out of equilibrium with the estimated natural state isotherms in the system.

The alteration mineralogy suggests that the system has always been dominated by near-neutral pH fluids, i.e., there are no indications of prior acid pulses in the system, unlike in some younger systems where reservoir acidity can be a constraint to production.

6.8. Production-Induced System Evolution

Since the onset of production in 2005, the San Jacinto field appears to have undergone a notable degree of change that can largely be related to field-wide pressure drawdown. Pressure drawdowns of <5 to ~50 bars have occurred between the natural state and 2018 conditions, which is comparable to the observed drawdown in other exploited geothermal fields. Injection regions in the north (SJ11-1 and SJ11-2) and south (SJ10-1 and SJ1-1) also display pressure declines, indicating the hydraulic connection of these regions to the production zone. Pressure drawdown is greatest in the east of the production area and lessens to the west. This variation may be the result of reservoir compartmentalization, as indicated by large pressure gradients between some wells. Marginal fluids may also provide increased pressure support in the west (supported by the changing chemistry of SJ4-1, SJ6-2, and SJ9-1); the east does not seem to receive the same pressure support, which is perhaps related to the thick low resistivity (low permeability) unit that is present there. While the pressure drawdown initially led to significant decline of some wells (which led to the make up well drilling campaigns since 2012), the field has now stabilised to a much slower decline along with more stable well production that is assisted by the wider distribution of production from the more recent step-out wells.

This field-wide pressure drawdown and associated deep reservoir boiling has resulted in the development of a steam-mobile two-phase region (steam zone) in the upper ~700 m above the primary upflow region (Figure 9 and Figure 10). This expansion manifests as an adiabatic temperature decline and the occurrence of high enthalpy steam feeds that have been witnessed in several production wells. Additionally, shallow steam kicks in the recent drilling campaigns, the ongoing expansion of surface thermal features in the central production area, and recent PTS logs all show that the steam zone continues to evolve and expand. If a suitable balance between deep and shallow production can be achieved, then it is possible that the surface features can be managed while continuing to develop the steam zone.

A competing phenomenon to the expansion of this steam zone is the incursion of marginal fluids and degassed outflow fluids that appear to be being drawn back laterally and downwards into the production area as a result of the pressure drawdown. The result of this incursion has been a temperature decline in the shallow reservoir (a separate process from the adiabatic temperature decline noted above) and a shift in the chemistry of some of the production wells, which largely appear to have stabilized. This chemistry shift is

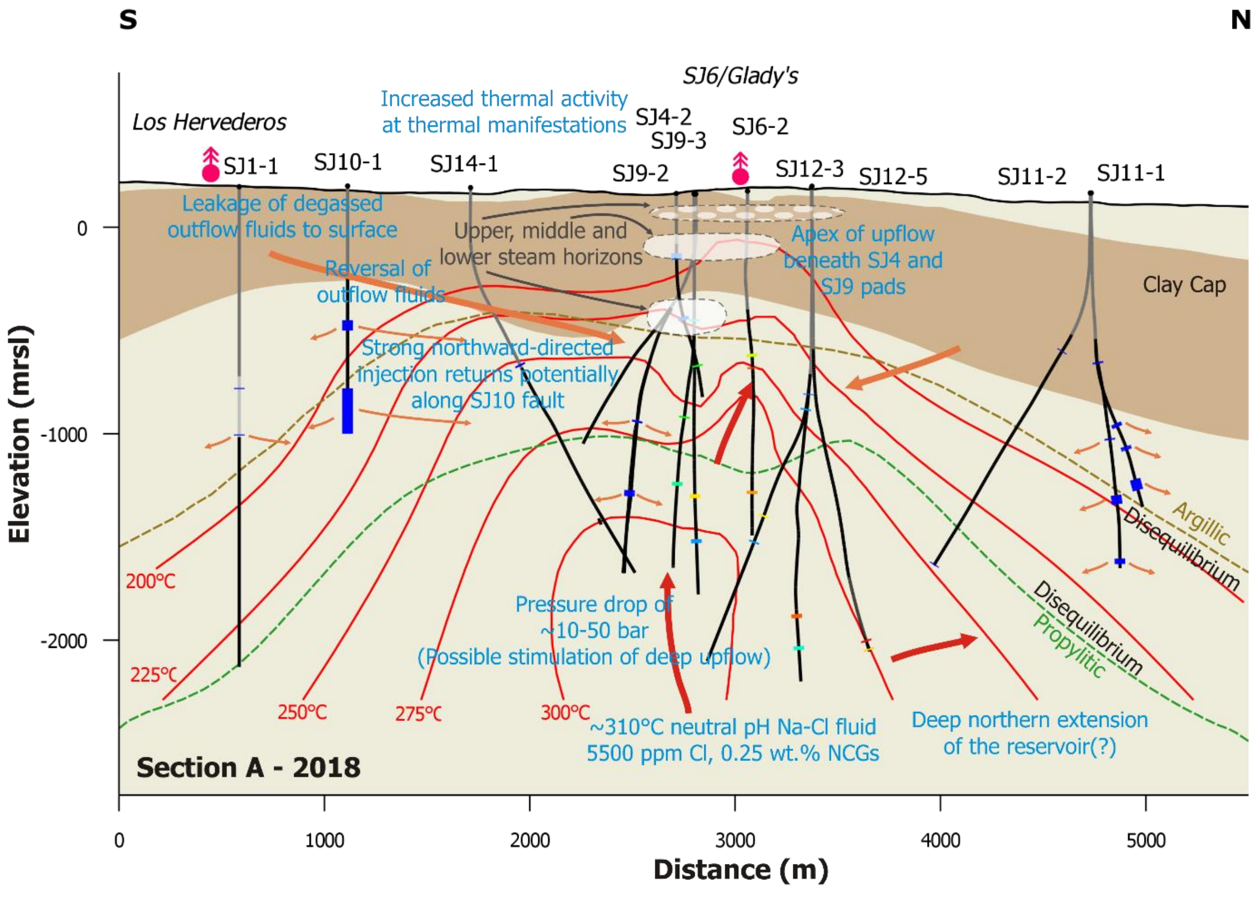

Figure 9: N-S cross section (A-A'; Figure 3) through the 2018 conceptual model for San Jacinto

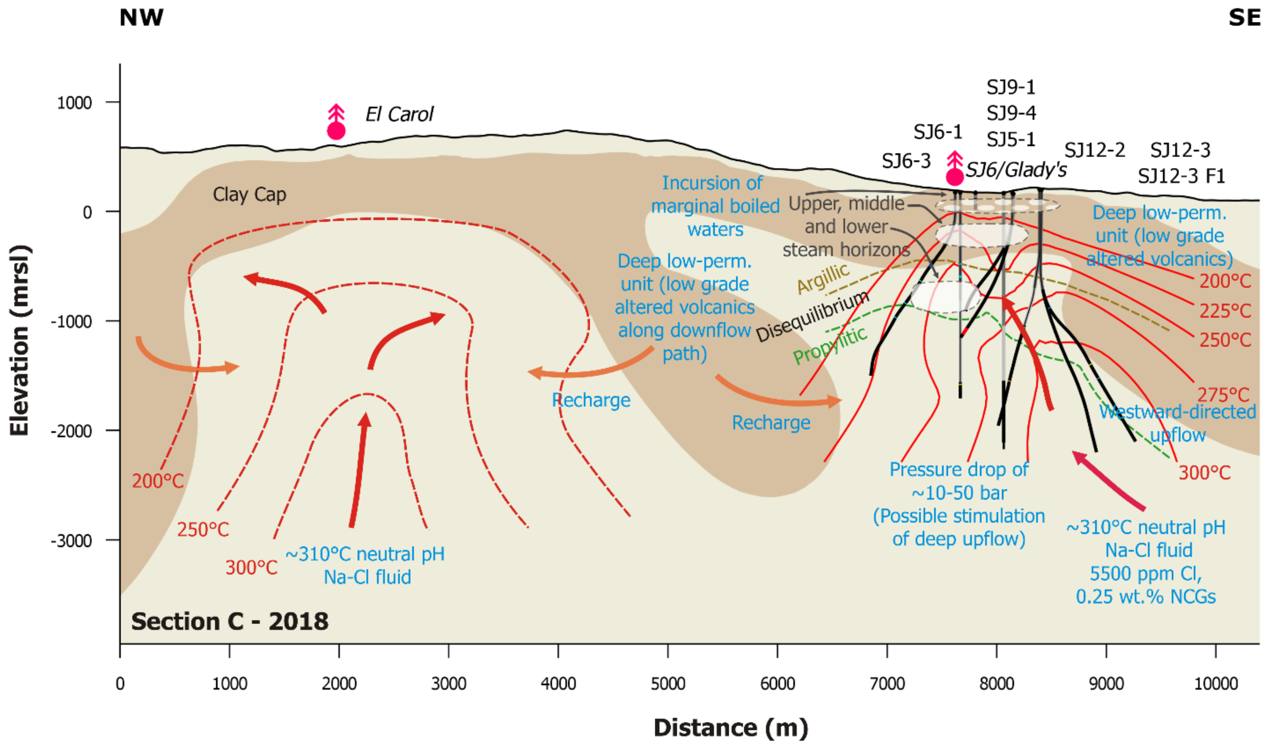

Figure 10: NE-SW cross section (C-C'; Figure 3) through the 2018 conceptual model for San Jacinto and the Western Sector

namely an increase in the chloride concentration of wells with shallow feed zones, e.g., SJ4-1, 9-1 and 6-2. The chemistry data illustrates that the process of recharge from outflow and marginal fluids started immediately upon the beginning of production in 2005, before injection in the south even began. A total temperature decline of 20 to >30°C has been experienced throughout the upper ~800 m of the reservoir, which includes declines associated with both the incursion of marginal/injection fluids and temperature declines from adiabatic processes. A particularly positive aspect is that there is no evidence of significant ingress of fresh groundwater or chemically adverse secondary fluids into the system (the latter which is known to occur is some fields with higher gas contents), since such a process can have a detrimental influence on well productivity and scaling potential. There has also been no production-induced increase in gas content of the fluid to the power plant.

The deep reservoir temperature at San Jacinto has remained fairly constant from natural state to 2018. A minor heating trend in the deep eastern regions of the system may be an erroneous artefact related to the degree of uncertainty that is intrinsic to the process of deriving the downhole PT interpretations. However, it is also conceivable that this apparent heating represents a real phenomenon related to the stimulation of deep hot upflow by pressure drawdown in the reservoir, which may serve to increase to overall capacity of the resource.

DISCUSSION

The progressive development of a robust integrated conceptual model for the San Jacinto – Tizate system has been instrumental for guiding a successful staged project development program. Supplemented with a comprehensive resource monitoring program it has been fundamental to recognising the potential implications of changes in resource characteristics, providing a sound basis for regular numerical model updates, and ultimately for informing resource management decisions such as make-up drilling strategies, optimization of the production and injection systems, or supplementary data collection activities to further improve resource understanding. More specifically, the main implications of the conceptual model understanding for ongoing successful field management at the San Jacinto – Tizate are:

1. ***Steam zone management:*** There is clear evidence that a steam cap continues to evolve above the deep liquid reservoir due to deep pressure drawdown and production. This provides an opportunity to access high enthalpy production using relatively shallow and cost-effective wells, while also seeking to mitigate the effects of increasing surface activity that poses a safety risk and could potentially threaten surface infrastructure.

2. ***Targeting production wells:*** While there is an opportunity to target the system steam cap for relatively shallow production, it is likely that some balance make-up drilling into the deeper liquid reservoir will be needed to maintain the ongoing process of deep system boiling to help drive sustainable production from the steam cap. Based on the current conceptual understanding the eastern side of the field between SJ12-5 in the north and SJ14-1 in south looks most prospective for deep make up production. SJ14-1 showed promising temperature and permeability indications before the drill string became stuck and the well had to be abandoned prematurely. The advantage of a well in the vicinity of SJ14-1 is that it is a part of the field that is less densely exploited and is distal from the inferred upflow zone where fluid temperatures above 300°C

have shown to have associated adverse impacts on permeability and silica management. An updated numerical reservoir model is under development to help inform future make up drilling strategies.

3. ***Informing injection strategies:*** In recent years injection has been largely focussed on outfield regions 1 – 1.5 km from the production area, supplemented with some limited injection closer to the production area. Tracer studies show that injection in the south has a much stronger connection to the production field than the north due to an inferred structural feature, the SJ10 Fault, that runs between the southern injection zone and the production area (Figure 3). Consequently, more injection was shifted to the north and appeared to have a positive effect on potential injection returns and in helping to stimulate development of the system steam cap. Ongoing monitoring will seek to attain the necessary balance between an appropriate level of system pressure support against the negative effects of premature injection returns.

4. ***Managing chemical constraints:*** Currently the main chemical constraint is associated with managing the brine produced from the north eastern SJ12 wells that produce from the hot (300°C) resource close to the inferred system upflow. These wells produce brine that is oversaturated with respect to amorphous silica and the brine requires acid dosing to inhibit silica scaling prior to being reinjected. The risk of acid inflows or calcite scaling is currently considered low based on observed system responses to the operating regime. These require ongoing monitoring particularly if adjustments to the production and injection configuration result in adverse effects such as premature injection returns or cool marginal water incursion.

5. ***Western Sector exploration drilling***: There is a well-formed conductive clay cap that updomes beneath the area encompassing the El Carol and El Najo surface manifestations on the northern flank of the Telica volcanic complex. The co-occurrence of a well-formed conductor overtop of a moderate resistivity core, the existence of flank thermal manifestations, and the young heat source beneath the Telica volcanic complex are all very positive attributes of this prospect.

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