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Multi-Disciplinary and Integrated Geothermal Exploration at the Pueblo of Jemez, New Mexico

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ABSTRACT

Trust lands of the Pueblo of Jemez, a federally-recognized Indian tribe, are located on the southwestern margin of the Jemez Mountains in north-central New Mexico. The most prominent feature in the Jemez Mountains is the 1.25 Ma Valles Caldera, one of the most intensively studied volcanic terrains in the world. The youngest intracaldera pyroclastic flows and lava flows were erupted between 55 to 40 ka. Numerous hot springs derived from the Valles Caldera discharge on the west and southwest edge of the caldera and down Cañon de San Diego, which is located three miles north of the Pueblo of Jemez. Indian Springs, on the banks of the Jemez River 3.5 km southwest of the Pueblo of Jemez village, is the southernmost known thermal spring related to the Valles system. The ongoing geothermal exploration project in the Pueblo of Jemez area characterizes the deeper geothermal potential suited for geothermal power production, in addition to known shallow geothermal resources. The project implementation plan has followed, and continues to follow, a logical and reasonable progression from geologic mapping, hydrogeochemistry and mineralogy to geophysical surveys to selecting a well site location. Drilling, logging, and well testing in the near future will be the final test of the viability of the resource.

Introduction

Prior to the project, no information about the location or extent of a potential geothermal resource commercially-viable for

geothermal power production was available in this study area. The study area, as well as its surroundings, show manifestations of multiple geothermal episodes, but no well exceeding 240 ft has ever been drilled. In this blind resource like scenario, this project was designed to image and explore through the shallow caldera outflow plume to depths of more than 3000 ft. A significant down-to-the-east normal fault, with 500 m of vertical separation, is buried beneath the floodplain of the Jemez River (Witcher, 2004) and appears to control the location of a possible geothermal target. Drilling west or east of the Indian Springs fault, can determine the success of a commercial power generation project, representing a substantial drilling risk (see Figure 1).

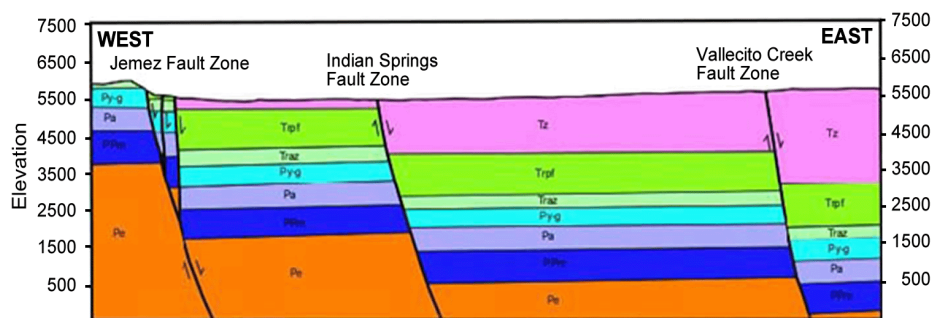


Figure 1. Geological interpretation before the project began in April 2010 (Witcher, 2004).

The Study Area

The Pueblo of Jemez is located along the Jemez River about 30 miles southwest of Los Alamos, New Mexico (see Figure 2). The Indian Springs are located just west of the Sierra Nacimiento, a prominent north-striking mountain range with both ancestral Rocky Mountain and a Laramide deformation history, and are southwest of the 40 ka -14 Ma Jemez Mountain volcanic field (JMVF). The southern Sierra Nacimiento and the JMVF are cut by north- to northeast-striking normal faults associated with Rio Grande Rift extension, which started in this area during Oligocene time (25-30 Ma; Kelley et al, 2011). Rio Grande Rift faults cut

JMVF rocks as young as 1.25 Ma (Smith et al., 1970) and appear to offset Quaternary river terraces (Formento-Trigilio and Pazzaglia, 1998).

The south-dipping bedrock consisting of Permian and Triassic sedimentary rocks outcrops in the southern Sierra Nacimiento west of the Jemez River on the Pueblo of Jemez. The late Paleozoic to Mesozoic rocks are unconformably covered by Cenozoic rocks, including the Oligocene to Miocene Gilman Conglomerate and Abiquiu Formation, Miocene Zia Formation, and Quaternary river terrace, travertine, and pediment deposits. Eolian and fluvial facies of the Zia Formation are poorly exposed to the east of the Jemez River. The Zia Formation forms good exposures only where the unit is well-cemented along fault zones. The Zia Formation is capped by terrace gravels east of the river.

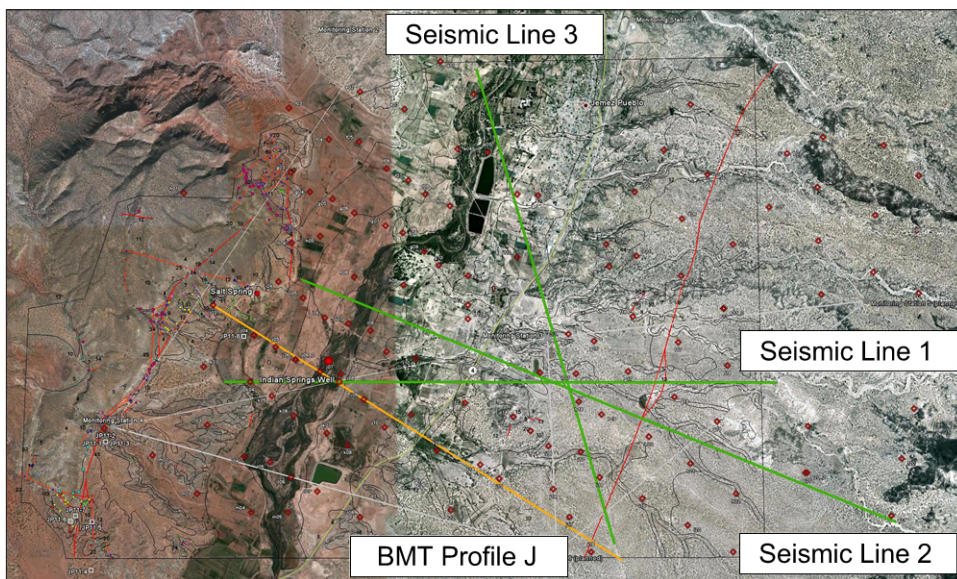


Figure 2. Study area surrounding the Pueblo of Jemez and mapped geological features as well as geophysical survey stations (seismic in green, magneto telluric in red, BMT Profile in orange).

Geological Mapping, Mineralogy, Petrography, Geochemistry and U-series Dating

Quaternary deposits along the Jemez fault zone, a rift-related fault west of the Jemez River, were sampled to ascertain the timing and intensity of past hydrothermal activity in the vicinity of Indian Springs. The sampled deposits include travertines preserved at three different strath elevations and a hematite coating on Quaternary pediment conglomerate and Triassic and Miocene sedimentary bedrock. X-ray diffraction was used to determine mineralogy, thin section work was used to establish whether secondary minerals related to hydrothermal alteration formed *in situ*, isotopic data on the carbonates was used to monitor changes in hydrothermal fluid chemistry through time, and U-series dating on travertine was used to constrain the timing of carbonate deposits associated with hydrothermal outflow plumes. The analytical results are briefly highlighted in the following paragraphs.

Quantitative mineralogical analysis of a sample from the Triassic Shinarump Formation sandstone indicates 85-wt % quartz, 10.4-wt % mica/illite, 4.3 wt % kaolinite, and traces of hematite. The quartz and feldspar grains are detrital in origin but the micro-

crystalline aggregates of silica, mica/illite, and kaolinite around the individual minerals and between the grains are products of hydrothermal alteration that formed *in situ*.

A carbonate-cemented lacustrine silty clay beneath the oldest travertine and a pediment conglomerate contains abundant quartz (32.1 wt %), calcite (40.4 wt %), and mica/illite (24.2 wt %) and trace amounts of kaolinite, hematite, and plagioclase. The feldspar grains disintegrated *in situ* during the hydrothermal alteration process, suggesting that the secondary minerals formed *in situ* and were not transported. The calcite mineralization is related to the overlying travertine deposit, which is dated to 223 ka.

The pediment conglomerate is mostly composed of feldspar and quartz that are embedded in finer rock fragments coated or cemented by hematite. The matrix is isotropic. Mica/illite and kaolinite formed *in situ* from the alteration of feldspar grains. Based on the clay mineral assemblage, the hydrothermal activity probably took place at higher temperature ($\geq 100^{\circ}\text{C}$) for illite to form in the presence of kaolinite and quartz (e.g., Sass et al., 1987). Hydrothermal experimental studies indicated that in the presence of increased potassium content possibly from the alteration of feldspars facilitated the formation illite at about 250°C (Yates and Rosenberg, 1998).

Quantitative mineralogical analysis of samples from the carbonate deposits indicated similar amounts of calcite, hematite, quartz, K-feldspar, plagioclase, and minor kaolinite. Hydrothermal fluids probably transported the minor amounts of felsic minerals, whereas kaolinite probably formed *in situ* from the alteration of detrital feldspars.

Despite minor differences of isotopic compositions, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ results are generally similar to each other. The isotopic compositions decrease from the old to the middle travertine deposits near Travertine Hill. The uppermost travertine near Salt Spring has slightly heavier isotopes compared with the older samples. These minor variations are also apparent in the mineralogical compositions. The isotopic and mineralogical compositions suggest that the travertine deposits represent sporadic pulses of hydrothermal activities during the Pleistocene consistent with the U-series dating results.

The U-series dating analyses of samples from the travertine deposits yielded late Pleistocene ages of 0.233 ± 0.0123 and 0.166 ± 0.0210 Ma on the older and younger travertine deposits, respectively. The middle travertine yielded an anomalous young age (144 ka) that is inconsistent with its stratigraphic position. The carbonate deposits on the west side of the Pueblo of Jemez represent pulses of at least three major hydrothermal outflow plumes related to the Quaternary Valles Caldera.

Figure 3 illustrates the stratigraphic relations among several of the collected samples in the vicinity of “Travertine Hill” located near the southern boundary of the Pueblo of Jemez (Figure 1).

Three additional sample of hematite mineralization were collected from Qp4 pediment conglomerate, Miocene Zia Formation

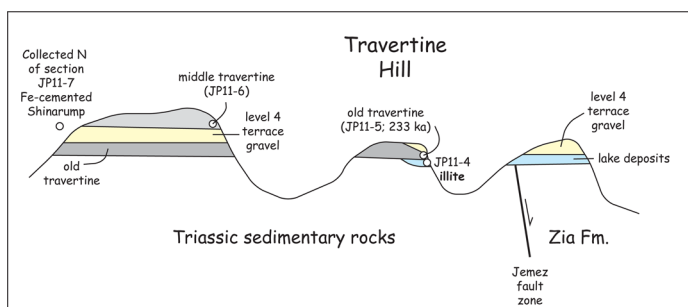


Figure 3. Schematic diagram of stratigraphic relationships near Travertine Hill.

and Triassic Shinarump Formation in Bluewater Canyon to the north. A younger travertine near Salt Spring crops out above late Pleistocene alluvium that probably represents one of the younger terraces (Qt5, ca. 50 ka) of the ancestral Jemez River flood plain. In summary, the sequence of Quaternary hydrothermal events recorded in the study area at Travertine Hill, Bluewater Canyon, and Salt Spring includes:

1. Deposition of a fine-grained, laminated, clay-bearing silty lake deposit with interbedded organic material across the Jemez fault zone. This lacustrine deposit contains illite, but it is not clear if the illite is detrital or if the clay grew *in situ*.
2. Deposition of the oldest travertine at ca. 233 ka.
3. Deposition of the Qp4 pediment.
4. Hematite accumulation within the Triassic Shinarump Formation near Travertine Hill. The Qp4 pediment, and Shinarump and Zia formations in Bluewater Canyon were likely mineralized at the same time, although the stratigraphic relations are less clear to the north. Illite formation accompanied hematite mineralization, suggesting temperatures $>100^{\circ}\text{C}$.
5. Deposition of the middle travertine on top of the hematite-altered Shinarump Formation near Travertine Hill. The middle travertine gave a ca. 144 ka U-series age, but the errors are large, so the age is considered suspect.
6. Accumulation of travertine along a NW-striking vent at ca. 166 ka near Salt Spring. This vent may have fed higher elevation travertine deposits north of Salt Spring. The vent appears to have been exhumed and is now surrounded by 50 ka Qt5 alluvium.

Geophysical Surveys

To obtain high-resolution images of subsurface geologic structures of the potential target geothermal reservoir at the Pueblo of Jemez, about 9 miles of active seismic reflection surveys were conducted along three lines using a static array of up to 400 channels at 50 ft source-receiver spacing (see Figure 4). Figure 5 shows the

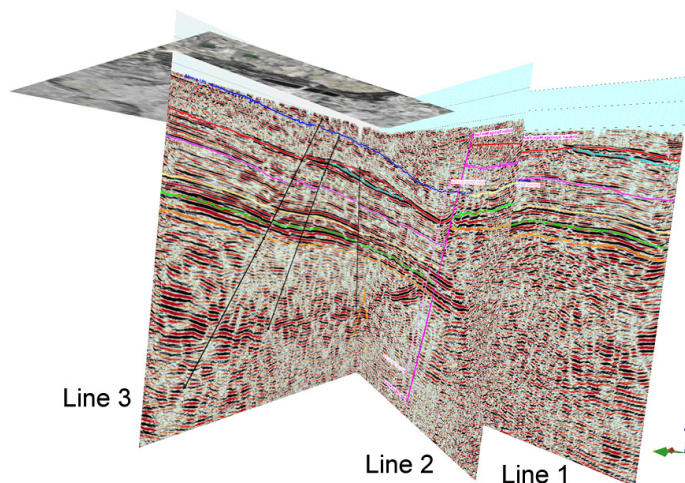


Figure 4. Seismic view from the northwest of the study area below the surface.

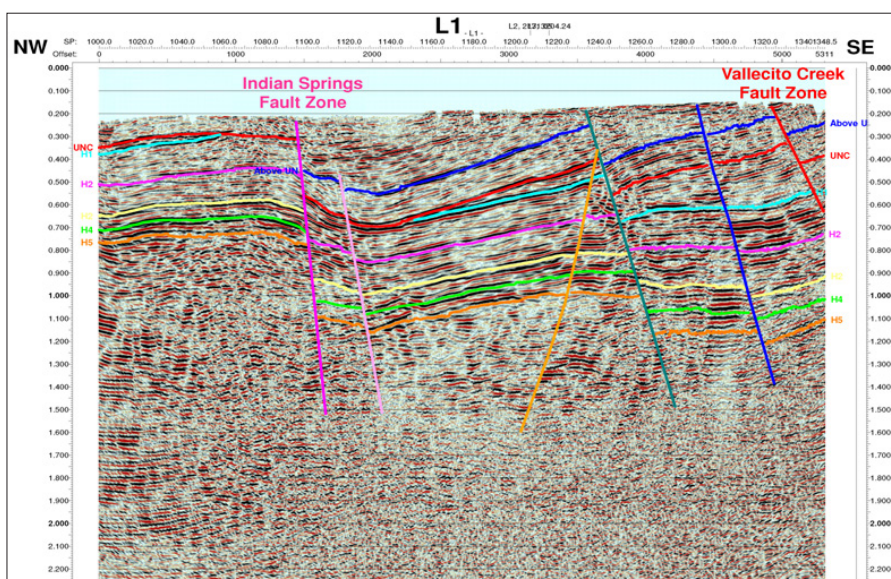


Figure 5. Interpreted Seismic Line 1.

time migrated, interpreted profile for Line 1. Kirchhoff migration and wave-equation migration have been processed after developing a velocity model in order to obtain a “true” depth of the profile.

For magneto-telluric (MT) imaging at the Pueblo of Jemez, we conducted 137 broadband MT (BMT) station observations resulting in 129 BMT 1-D inversions, 1 BMT 3-D rendering from 1-D data (1.5-D inversion), 13 BMT 2-D inversions (profiles), 1 BMT 3-D rendering from 2-D data (2.5-D inversion), and 6 unconstrained BMT 3-D inversions. We also conducted 25 long-period MT (LMT) station observations with 24 LMT 1-D inversions and 14 LMT 2-D inversion profiles. A total of 162 MT stations (both BMT and LMT) were used for observation, and 153 of them were used for inversion. The receiver frequency range for LMT stations is 100 Hz to 0.0001 Hz and the frequency range for BMT is 1000 Hz to 0.001 Hz.

The distribution of electrical resistivity in the subsurface based on the processed inversions and in comparison with the seismic results shows a favored high conductivity deeper aquifer location

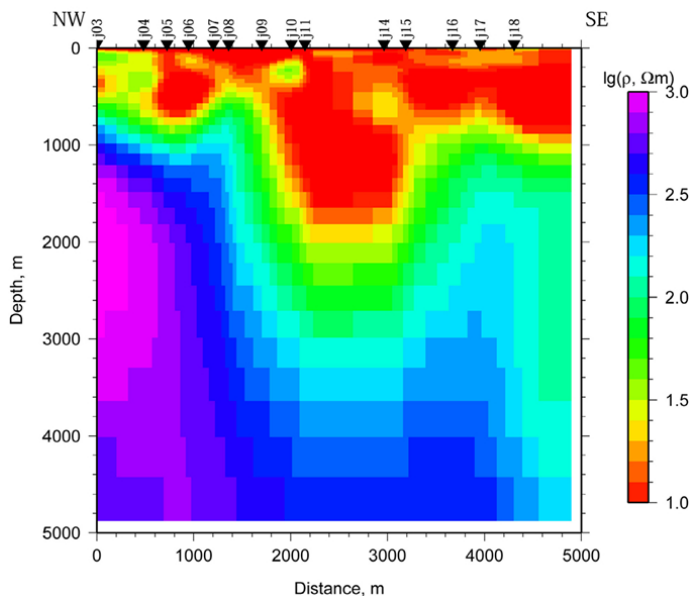


Figure 6. 2-D inversion of BMT Profile J showing a highly conductive zone reaching at least 1800 m deep and confirming the steep and deep fault structures visible in seismic lines L1 and L2 as well.

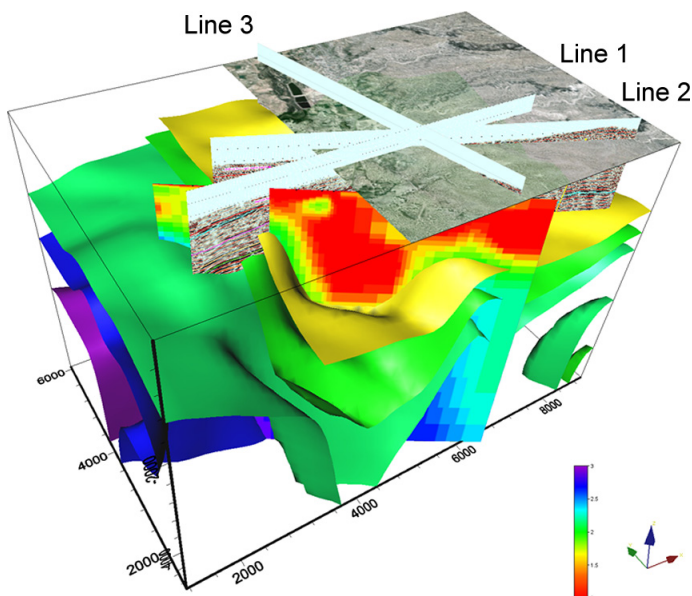


Figure 7. 3-D integration of seismic and 2.5-D magneto-telluric data and the 2-D BMT Profile J. The “cup” as identified in the 2-D inversion of BMT Profile J.

or suitable entry point into a deeper aquifer. In the following section, this location is described as the “cup” (see Figure 6).

Figure 7 shows the 3-D integration of seismic and 2.5-D magneto-telluric data and the 2-D BMT Profile J. The “cup” as identified in the 2-D inversion of BMT Profile J. Figure 8 shows a close-up into “the cup”.

Integrated Analysis of Results

Figure 9 (top) is an interpreted east-west cross-section that combines the results of geologic mapping with the seismic and

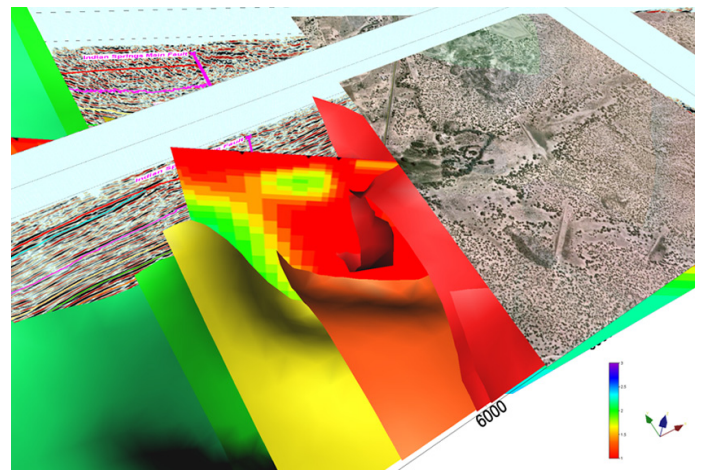


Figure 8. Close-up into “the cup” showing integrated seismic fault interpretation and magneto telluric data.

magnetotelluric data. The western third of the cross section across the Jemez fault zone is based on geologic mapping and the eastern two thirds is based on interpretation of Seismic Line 1. The rock units on the cross section were assigned using the relative reflectivity of units on the seismic lines and published thickness data. Thickness was measured upward from the Great Unconformity between the Proterozoic basement rocks and the Mississippian to Pennsylvanian sedimentary rocks. The lowest set of strong reflectors is interpreted to be Mississippian to Pennsylvanian carbonates. The seismically more transparent unit above the strong basal reflectors is likely the Abo Formation, which in this part of the Jemez Mountains is mainly siltstone with a few interbedded channel sandstones and conglomerates. The higher strong reflectors are interpreted to be Permian Yeso Group and Glorieta Sandstone, and Triassic Moenkopi Formation and overlying Shinarump Formation of the Chinle Group. Units above the pronounced unconformity on the Triassic rocks may include syn-Laramide Eocene Galisteo Formation (Tg), the Oligocene to Miocene Gilman Conglomerate and Abiquiu Formation (Tgc+Ta), and the Miocene Zia Formation (Tz).

The area outlined in yellow on the cross section shows the projection of the magneto telluric anomaly located about 0.25 mile south of the section line onto Seismic Line 1, scaled appropriately. Jurassic units, most notably the Jurassic Todilto Formation, which contains gypsum and limestone, are not present in this area, so the anomaly may be hot water rather than gypsum-saturated water. Magneto telluric anomalies are not observed north along strike of the Indian Springs fault. Along south the survey boundaries are reached with potential inversion borderline limitations. The localized anomaly may be related to restricted, relatively recent, rupture along the fault.

Witcher (2004) had previously proposed that the warm water observed at Indian Spring and in JP-1 was localized as a consequence of juxtaposition of aquifers and aquitards, creating hydrogeologic windows. Such a model would predict a relatively restricted stratigraphic range for the magnetotelluric anomaly. The fact that the anomaly cuts across stratigraphy suggests pervasive fracture porosity and permeability, assuming that the anomaly indicates hot water.

Past and present geothermal systems: Stratigraphic relations among travertines associated with the Jemez fault zone and other faults in the southwestern Jemez Mountains indicate multiple (at least four) episodes of travertine deposition. The travertine deposits place some constraints on the timing of high-temperature (>100°C), illite-forming hematite alteration near Travertine Hill. The Qp4 pediment conglomerate was deposited after 233 ka. Hematite alteration near Travertine Hill occurred prior to deposition of the middle travertine. The hematite alteration is poorly constrained to be older than 144 ka. Thus, this mineralization is relatively old.

The hydrogeochemical data gathered, as part of this investigation with analyzed geothermometry and standard stable isotope data, supports an outflow plume dominated system west of the Indian Springs Fault zone and indicates that the fluids observed in the Indian Springs well itself are of shallow origin; the shallow Valles Caldera outflow plume is at a depth of about 240 ft and a temperature of about 68°C.

The Conceptual Model

Figure 9 summarizes the conceptual model for the resource, which builds on the model of Goff et al. (1988) and includes a shallow outflow plume and a deep convection system. The latter system, which is blind, holds the greatest possibility of commercial power production. The geologic cross-section runs down the Jemez River between Sulphur Springs and San Ysidro. The geology is reasonably well constrained by recent 1:24,000 scale geologic mapping (Goff et al., 2005; Kelley et al., 2003; Osburn et al., 2002; Pazzagila et al., 1998) and borehole data (VC1, VC2a, VC2b, JS1) north of Red Rocks. The isotherms are constrained by borehole data between the caldera and Jemez Springs (JS1). Older rock units along the river south of Red Rocks are buried by Quaternary floodplain deposits, but their depth and displacement can be loosely constrained, in part, by the interpreted seismic lines. The shallow outflow plume from the Valles Caldera can be mapped as far south as JP1 on the Pueblo of Jemez (orange dashed line in Figure 9, bottom). Temperatures at depths greater than 254 ft south of JS1 in Jemez Springs are not known. The projected depth of the 100°C isotherm on the south end of the cross section is based on a few BHT data and one equilibrium temperature log from oil wells several kilometers west of San Ysidro on the Colorado Plateau. The red line shows the approximate position of the 100°C isotherm using the Jemez Springs and San Ysidro data as end points.

A speculative model of deep temperatures in the southwestern Jemez Mountains is depicted by the dashed red

line (see Figure 9 (bottom)). This testable hypothesis is based on temperature-depth observations of Harrison et al. (1986) at Fenton Hill and Shevnell et al. (1988) in AET-4, which is located just northeast of Jemez Springs on the downthrown side of the Jemez and Cat Mesa fault systems. T-D data from Fenton Hill show lateral flow of hot water at the Proterozoic-Late Paleozoic contact, T-D data from AET-4 shows lateral flow of 120°C water within the Madera Limestone, about 100 m above the basement contact. Although no lateral flow at the basement contact is observed at Jemez Springs (Goff et al., 1988), it is possible that deep, south-directed lateral flow has stepped east of the Cat Mesa and Jemez fault systems and is now migrating south along the Vallecito and Jose fault systems.

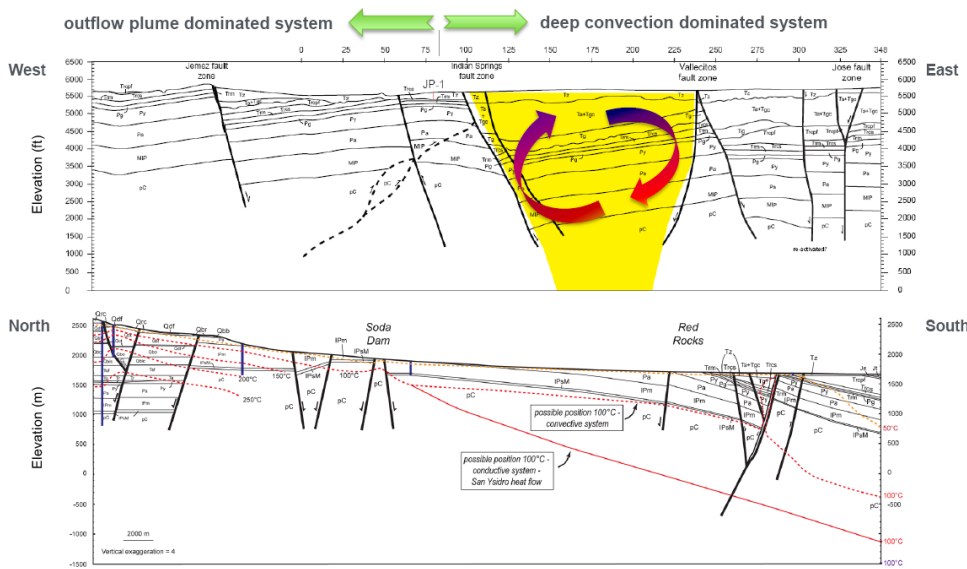


Figure 9. (top) Geologic interpretation of Seismic Line 1. The yellow area is the projection of the magneto telluric anomaly onto Line 1. (bottom) Conservative temperature isotherm modeling based upon BHT data in the Colorado Plateau and the upper Valles Caldera system.

Drilling Planning

Currently the project is undergoing detailed drilling planning. A first potential bore hole course has been derived that tries to take advantage of several known and identified permeable structural elements – fault zones and the often weathered top zone of the Precambrian (see Figure 10). The bore hole course is currently suggested based on optimum offset from the Indian Springs fault

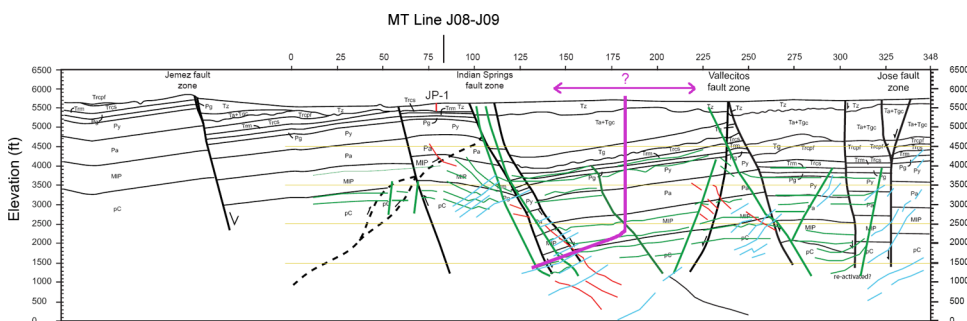


Figure 10. Potential drilling path based upon the conceptual model and early stage wave field separation imaging interpretations.

zone, relative location to the highly conductive area identified through magneto telluric and (labeled “the cup”) and logistic practicalities, including the drilling budget. Completion design for the drill hole after deviation from vertical will provide as much open hole as possible.

Early stage wave-field separation imaging (Huang et al. 2011) potentially highlights additional faults and deeper ranging faults than in the initial geological interpretation of the time, Kirchhoff and wave-equation migrations. Crossing through the complete Indian Springs fault zone consequently has a high potential for encountering higher temperature fluids entering the circulation system from below.

Conclusions

This project has already discovered many prior unknown and promising details about the geothermal processes in a study area located near the Valles Caldera that preserves evidence for many geothermal episodes during the last 500 ka. A deep convection dominated resource in this blind like resource scenario appears to have been identified through data integration and explained through a conceptual model. The existence of this deep geothermal resource commercially-viable for geothermal power production is very likely. Drilling the first exploration well in the area to a depth of up to 6000 ft will reveal additional information and help explain the nature of this deep resource.

Acknowledgements

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