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Exploration results and resource conceptual model of the Tolhuaca Geothermal Field, Chile

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ABSTRACT

An exploration program conducted by GeoGlobal Energy Chile (GGE Chile) at its San Gregorio concession, including geology, geochemistry, T-MT-AMT and deep core hole drilling to 1073 m depth, discovered a geothermal resource and constrained the preliminary resource conceptual model at Tolhuaca volcano. Early reconnaissance exploration indicated the presence of a geothermal system based on cation geothermometry from mixed chloride springs of 160°C and gas geothermometry from the Muro fumarole of 220 to 250°C. Following several years of surface access negotiations, a detailed T-MT-AMT geophysical survey was completed while a helicopter-supported core hole rig was mobilized in early 2009.

Geologic mapping and detailed geochemical sampling were run in parallel with the 70 station T-MT-AMT survey. The T-MT-AMT was optimized to effectively acquire data in the rugged, relatively inaccessible terrain on the glaciated lava flows covering much of the prospective area. The first 10 T-MT-AMT stations showed that the Muro fumarole located 1800 m to the south of the more easily accessed Sola fumarole was closer to the most intensely altered part of the clay cap, and the initial well location was shifted to that area while the rig was mobilizing. The low resistivity clay encased a resistive zone that, in conjunction with the gas chemistry, was interpreted to be a permeable steam cap.

The well Tolhuaca-1 was continuously cored to 1073 m depth. Drilling paused for a flow test demonstration of the shallow 150°C to 160°C steam reservoir between 120 m and 320 m depth. At 1073 m, the declining temperature gradient and propylitically altered rocks are consistent with a conventional >289°C permeable geothermal reservoir with neutral pH and low gas content, implying that power generation from this resource would have low CO_2 emissions. The T-MT-AMT survey imaged a >10 km^2 low resistivity clay cap that extends beyond the known fumaroles on the lower flanks of the glaciated volcano. Although the shallow zone is hot enough to support binary or low pressure flash geothermal power generation, GGE Chile's first priority will be targeting additional wells to produce the greater than >289°C reservoir.

1. INTRODUCTION

The Tolhuaca Prospect is located on the NW flank of the heavily glaciated, young but inactive Tolhuaca Volcano in southern Chile (Figure 1). Regional geochemical reconnaissance by Hauser (1997) and Urzúa-Monsalve and Powell (Powell, 2003) of hot springs in adjacent valleys noted the potential for high temperature systems in the area. In 2004, opportunities for acquiring geothermal concessions coincided with increasingly favorable electricity market conditions for geothermal development in central and southern Chile and led to an application for a geothermal concession. In subsequent geochemical exploration two fumaroles on a volcanic ridge NW of the volcano were discovered (Melosh, 2006). Geochemistry of the fumaroles and hot springs suggested that a geothermal system suitable for power production might occur near the Tolhuaca volcano. A reconnaissance MT survey in the valley and lower flanks of the volcano mapped the Miocene basement granites that that outcrop at elevations of between 1350 m and 1700 m between 3 and 7 km to the north, NW, and SE of the present-day volcano.

When surface access agreements seemed likely to be resolved at Tolhuaca in December 2008, GGE Chile implemented a plan to demonstrate a geothermal resource before the winter snows closed access, probably by May 2009 (Melosh et al., 2009). The Tolhuaca field is 6 km from the nearest drivable road over rugged. An all-weather road would take months to arrange and construct. Therefore, the only physical access options for exploration in the available time were by foot, horse, or helicopter. This dictated the use of a helicopter portable rig. The most effective data set for targeting a well given the access and timing constraints was likely to be a fast, reliable, non-profiling resistivity method like MT coupled with early results obtained from ongoing geochemistry and geology studies.

Following a review of the geochemistry that generated the initial interest in the prospect, the rationale for using the T-MT-AMT approach to image resistivity introduces the resistivity imaging results. The resistivity images illustrate the expectations for targeting the first well and introduce a comparison between the predicted and observed resource properties in well Tolhuaca-1. The integration of the temperature and geology results from Tolhuaca-1 with the surface geoscience data support an interpretation of a shallow >150□C reservoir and a deep ~300□C reservoir. The deep target will be drilled in 2010.

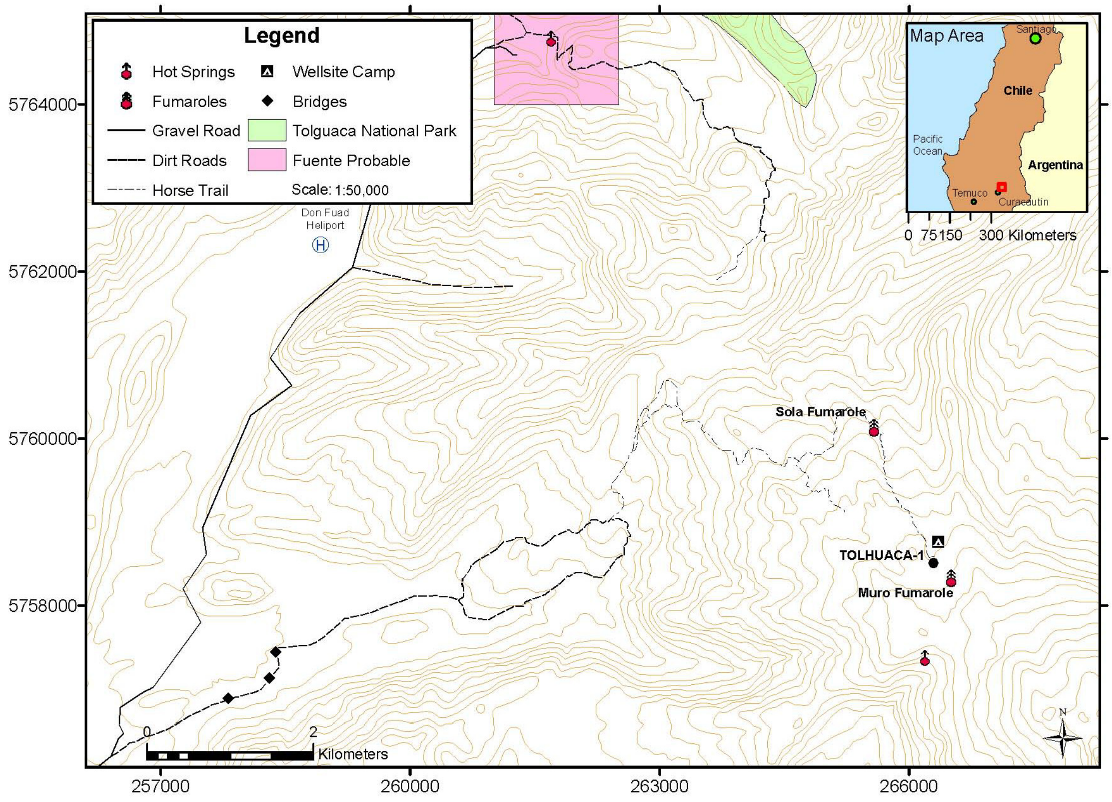

Figure 1. Location map for Tolhuaca.

2. PRE-DRILLING GEOCHEMISTRY AND GEOLOGY

Three geochemistry surveys conducted between 2005 and January 2009 assessed hot springs and fumaroles on the flanks and surrounding the volcano. The superheated Sola and Muro fumaroles were identified 1.8 km apart along a NNW trend of eruptive vents NW of the volcano (Figure 1). The active Lonquimay Volcano, which last erupted in 1990, occurs along this same trend 22 km to the SE. A boiling temperature artesian hot spring occurs at the Termas Tolhuaca about 6 km NW of the fumarole areas, outside an arcuate fault that bounds the young volcanism on the north and west sides. No tuff deposits have been correlated with this structure to demonstrate a caldera. Two more hot spring areas, Chilpa and Valle Vista, are located in older volcanic and intrusive rock 10 to 15 km north of the prospect area.

The fumarole and hot spring analysis showed evidence of a neutral high temperature reservoir (Melosh, 2006). Hot spring water from the Termas Tolhuaca showed Cl-HCO_3 chemistry and cation geothermometry of about 160°C. Gas from the boiling Termas spring suggested higher temperatures but the gas geothermometry was considered unreliable due to the abnormally high H_2S gas composition. Another gas analysis was available from the southernmost fumarole (Muro) on the flank of the volcano (Figure 1), which showed more typical volcanic area geothermal composition and geothermometry from 220° (H_2/Ar – CO_2/Ar) to 250°C (FT-HSH). Although some of the gases were below detection (e.g., CH4 and NH3) the others indicated at least partial geothermal reservoir equilibrium.

The preliminary conceptual model suggested that the Muro fumarole could be related to a steam cap and that Termas Tolhuaca was influenced by mixing with condensate. Detailed follow-up sampling in 2009 included two more fumaroles and nine hot springs. Although most of the newly sampled hot springs were not analyzed prior to drilling, field measurements suggest that they are heated meteoric water mixed with some steam condensate, consistent with the proposed model. The new fumarole gas and well flow-test sample analyses are expected to more accurately constrain the expected range of high temperature reservoir conditions.

Liquid samples from the Chilpa and Villa Vista springs to the north show dilute bicarbonate and sulfate chemistry with geothermometry roughly in agreement at about 130ºC. These types of springs are typical at intermediate elevations in geothermal systems and commonly occur in southern Chile along the volcanic arc. They reflect shallow heating and probably lateral transport of meteoric and condensate water but do not appear to be immediately related to a high temperature system.

3. MT RESISTIVITY SURVEY

There are many published case histories of the use of the magnetotelluric (MT) method in geothermal exploration because it is usually the lowest cost method to reliably image resistivity to depths greater than 1000 m (Cumming and Mackie, 2009). Because the clay alteration that caps geothermal reservoirs is low resistivity, MT can map the cap and, by association, the reservoir.

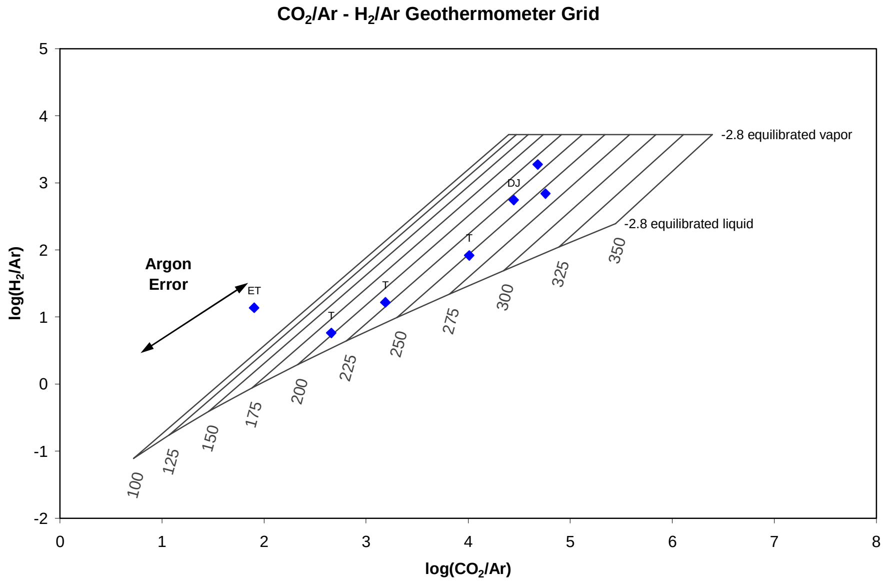

Figure 2. H_2/Ar – CO_2/Ar gas geothermometer cross-plot showing Muro fumarole (DJ) and Termas Tolhuaca (T) samples

3.1 T-MT-AMT resistivity survey design

MT is a passive method, using natural electromagnetic waves to image resistivity at depth. Although local lightening is a noise source for MT, distant thunderstorms around the world provide the higher frequency signals from 1 to 10000 Hz, allowing MT to image resistivity from a few m to about 1000 m. MT signals at frequencies lower than 1 Hz, roughly corresponding to depths of investigation greater than 1000 m, originate from solar flares associated with sun spots. Charged particles sent at high velocity into space from solar storms collide with the earth's magnetosphere and create the electromagnetic waves detected by MT below 1 Hz. Solar sunspot activity waxes and wanes in an 11 year cycle. The last solar maximum was in 2001 and another is due in 2011-2012. Unfortunately for the Tolhuaca MT survey, in 2008 and early-2009, NASA recorded the lowest solar activity since 1913. When signal levels are very low, even modest noise levels related to distant electrical facilities that would not have caused a problem in average sunspot conditions can be troublesome. Although longer recording times can often mitigate the problem, the low solar activity made MT less reliable below 1 km depth during the early-2009 survey at Tohuaca.

At Tolhuaca, access limitations constrain MT station distribution in a way that would limit analysis to a 1D approach, effectively limiting the reliable depth of investigation to the base of the clay cap. Because granites were exposed on the lower flanks of Tolhuaca Volcano, it seemed likely that the conductive cap of altered volcanic section would be less than 1000 m thick. Given the low MT signal level expected for the 2009 survey, the high regional cultural noise from hydroelectric power plants in the region, the difficult access conditions, and the relatively low depth of investigation that might be needed, GGE Chile considered resistivity sounding methods other than MT.

Options at Tolhuaca were limited by access, topography and the possibility that reliable resolution to greater than 1000 m might be needed. Methods like CSAMT (Urquhart and Zonge, 1997), VES (Risk et al, 1988) and TEM (Arnason et al., 2005) use active sources and are often more effective in areas with electrical noise but, to resolve resistivity below 1000 m, they require very large generators and long transmitter cables, problematic issues in terrain like Tolhuaca. The MT method has many variants applicable to specific circumstances. One version called T-MT measures at least one MT station with telluric stations that are just MT stations where only the electric field is measured, assuming the magnetic field is similar (Hermance and Thayer, 1975; Stodt et al. 1981). This reduces costs and improves accessibility since heavy magnetometers need not be carried. AMT is another commonly used option that is just T-MT recorded above 0.1 Hz using lighter equipment for a few hours instead of for more than 12 hours, as is typical for MT. The survey contractor, Wellfield Services, was able to respond to a survey specification to mobilize equipment for and adjust field programs to acquire MT, T-MT or AMT as the need arose.

To optimize the MT acquisition rate, reduce costs and provide flexibility in the field, the survey was designed to provide three modes of operation. The survey would begin with standard MT recorded from 0.001 to 10000 Hz. If information deeper than 1000 m was being reliably resolved, it would switch to recording T-MT, with telluric-only stations recorded at stations where rugged access was an issue or glaciated surface lavas made installing magnetometers difficult. However, if little useful data was recorded below 1 Hz, then the survey would switch to record AMT with telluric stations. To address the low signal levels and high regional noise, all of the data would be recorded for 12 hours overnight, even the AMT. This flexibility proved to be effective. The low signal and high regional noise made both MT and AMT unusable below 1 Hz and so most of the survey was recorded as AMT.

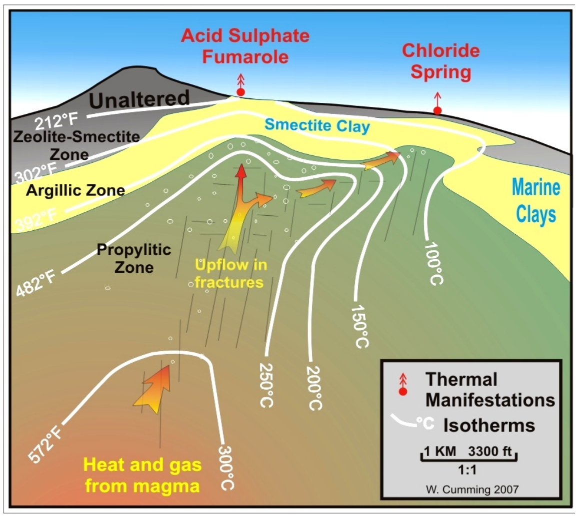

Figure 4. Conceptual model cross-section generic high temperature geothermal reservoir, including isotherms defining the thermally convective reservoir with fracture permeability capped by the impermeable, thermally conductive hydrothermal clay.

3.2 Conceptual goals of the geothermal resistivity survey

Numerous geothermal case histories have established the conceptual basis of resistivity interpretation in geothermal exploration (Cumming, 2009). In high temperature geothermal fields, the most prominent resistivity feature is usually the low permeability, low resistivity clay cap that overlies the high permeability, high temperature productive reservoir (Figure 4). The argillic alteration zone that forms the cap contains smectite and mixed layer smectite-illite clay that have a high cation exchange capacity and very low resistivity, typically ranging from 1 to 10 ohm-m (Ussher et al., 2000). Because smectite is temperature sensitive, it progressively transforms into illite over a temperature range of 70 to 220ºC. The propylitic alteration of a permeable reservoir at >220ºC is dominated by more resistive clay types like chlorite and illite and typically has a resistivity range of 10 to >200 ohm-m but most commonly 20-50 ohm-m, much higher than the shallow argillic cap of the system.

Besides plugging pore throats, smectite and smectite-illite clays in relatively small amounts change the mechanical properties of rocks and inhibit the creation of permeable open fractures when faults penetrate the argillic alteration zone. By comparing borehole imaging logs to total clay content, Davatzes and Hickman (2009) showed that very high clay content, even if not smecitite, also tends to inhibit the creation of open space permeability by fracturing. Therefore, although low resistivity related to smectite alteration is a reliable indicator of low permeability, while the higher resistivity related to other clays is more ambiguous.

3.3 MT resistivity survey results

Following the initial geochemistry and geology reconnaissance projects, an initial 19 station MT survey was collected by GNS Science of New Zealand in 2007 to establish background resistivity patterns between the Tolhuaca Volcano and the thermal manifestations at more accessible lower elevations to the north. These stations mainly detected resistivity greater than 1000 ohm-m, indicating that the chloride and mixed hot springs were due to either a low temperature outflow within or just above the shallow granite or were unrelated to the Tolhuaca prospect.

In 2009, 80 more stations including 7 MT, 10 T-MT and 63 AMT stations were located on and close to the Tolhuaca Volcano. Almost all of these detected hydrothermal clay alteration as illustrated by the map in Figure 5, showing 1D conductance to 400 m depth and the location of the stations relative to the fumaroles. Conductance is the inverse of resistivity averaged over a depth interval and is a rough analogy to total smectite clay to that depth. The cross-section in Figure 6 shows the resistivity distribution relative to the well, Tolhuaca-1.

3.4 MT resistivity and well targeting

The cross-section in Figure 6 was initially produced from the first stations emailed from the field as “high priority” stations. Besides identifying whether the rest of the survey would be acquired as T-MT or AMT, these data were urgently required to choose the drilling site for the rig that was being mobilized at the same time. The two available drilling location options were near the Muro and Sola Fumaroles. Figure 6 indicated that the location near the Sola Fumarole to the north was apparently close to the edge of the shallow geothermal system, indicated by the rapid thickening of the low resistivity (red) smectite alteration to the north. Therefore, a cellar was constructed close to the Muro Fumarole to the south.

The resistivity cross-section also shows that the clay alteration appears in bands. The large green area encased in red below station T78 at about elevation 1700 m was interpreted as a likely steam cap, with possibilities of similar zones shallower, and the drilling crew were alerted to this possibility. The well encountered and tested a dry steam zone reasonably close to the expected elevation. The base of the smectite clay appears to be flat lying, suggestive of a lithological control rather than an alteration pattern closely following a temperature contour, as commonly occurs in volcanic geothermal systems.

4. Tolhuaca-1 Well

The Tolhuaca-1 core hole drilled through an upper volcanic section (0-650 m) composed of andesitic lava flows and volcaniclastic breccias and then through an underlying thick sedimentary sequence with interspersed lava flows to TD (650 m-1072.8 m) (Figure 7). Secondary hydrothermal alteration is characterized by two zones of intense argillic alteration in the upper ~700 m of the core, gradually transitioning into propylitic alteration from ~700 m to TD. The hydrothermal alteration rank increased from argillic to propylitic in a manner consistent with measured temperatures (Figures 7 and 8).

The andesite lava flows in the upper volcanic sequence are intercalated with volcanoclastic breccias that were probably produced by a syn-emplacement autobrecciation process, where differential cooling and brecciation of lava flows occurs when the flows come into contact with the atmosphere. The underlying sedimentary sequence consists of an upper unit of interbedded sedimentary breccias and mudstones (650-730m) overlying a lower unit of sedimentary conglomerates interspersed with andesite lava flows (730-1072.8m).

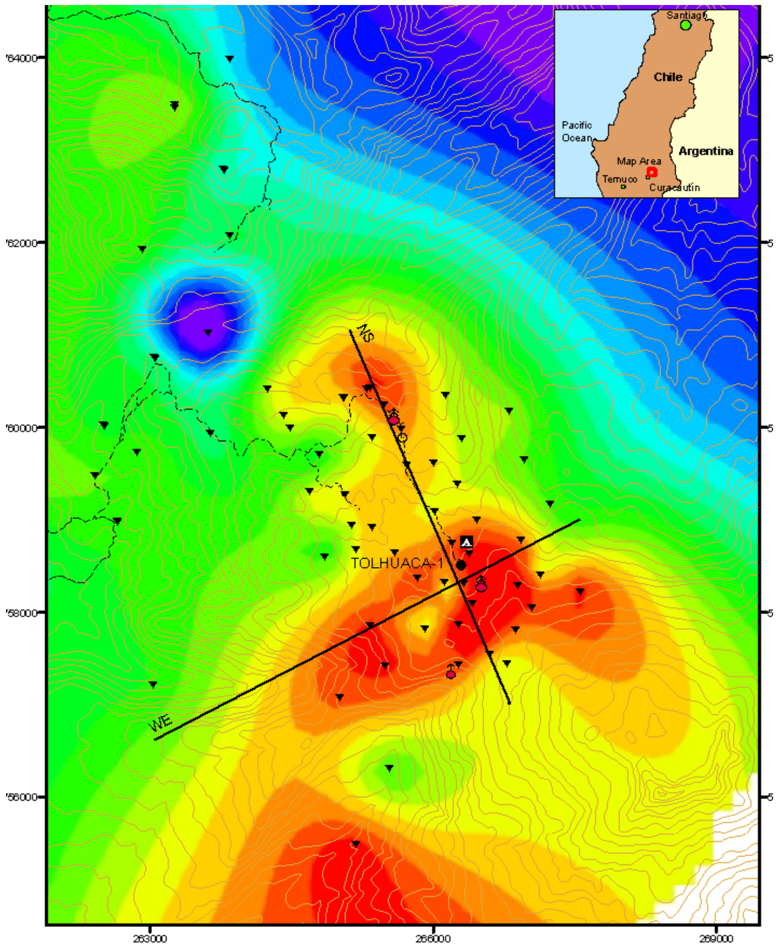

Figure 5. MT conductance to 400 m depth

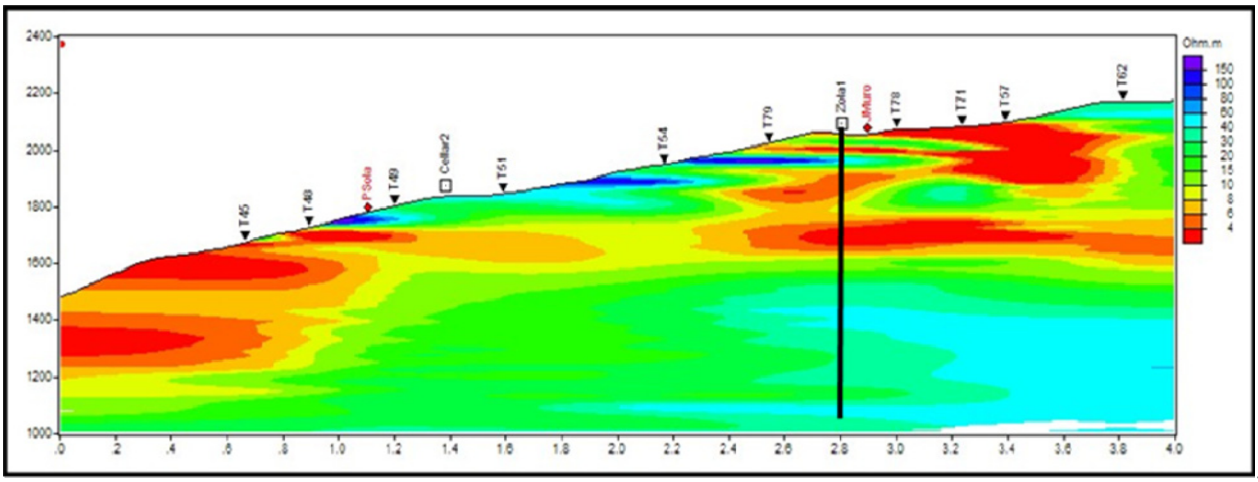

Figure 6. MT resistivity cross-section N-S with MT stations, fumaroles and well Tolhauaca-1

NOTE TO EDITORS: Because the well was only recently completed, the isotherm model and well geology overlays are still being updated but will be added before October.

Argillic alteration facies are characterized by Fe-oxides + chlorite + calcite + clay ± quartz ± pyrite, whereas high temperature propylitic facies at depth are delineated by the occurrence of epidote, and propylitic alteration is generally characterized by chlorite + epidote + calcite ± pyrite ± quartz ± zeolites mineral assemblages (Figure 7). Epidote first appears as a fracture-filling secondary mineral in a conglomerate host at 728 m, but appears in the matrix of sedimentary units and as vesicule-filling lava flow units deeper downhole. Shortly after the appearance of epidote at 728m, veins of kaolinite clay were identified by methylene blue analysis at depths of 782 m and 916 m.

The intense argillic alteration correlated closely with low resistivity zones from the closest MT stations. The transition from the low resistivity argillic zone to a more resistive chlorite zone at 400 m depth also correlated very well with the MT data. However, this transition was over

600 m higher in elevation than the interpreted transition to the >289ºC permeable reservoir. Such separations are commonly observed and can be fit with several models. For example, the chloritic zone may correspond to a section of volcanic sediments that have relatively high clay that inhibit the formation of fractures. In any case, the large separation implies that the smectite cap is more indirectly associated with the underlying >289ºC reservoir than is usual, implying in turn, higher risk in well targeting and resource assessment.

The shallow steam cap interpreted from the MT was encountered in the well and tested after drilling to 161 m. The shallow 150 to160ºC reservoir apparent between 120 and 320 m in the temperature profile was sampled during the flow test and is expected to be directly related to the fumarolic system.

Well temperatures measured while drilling included several initial measurements using maximum reading thermometers (MRT) and nine subsequent temperature profiles from digital Kuster log data (Figure 8). Measured temperatures revealed that, below the shallow steam reservoir at about between 120 and 320 m, a steep conductive temperature gradient is maintained in low permeability rocks nearly to the bottom of the hole where the maximum temperature of 289ºC was recorded (Figure 8).

Another reservoir is likely to be found just below the bottom of this well. The decrease in the temperature gradient at the bottom of the well from 20ºC/100 m to 8ºC/100 m shown in Figure 8 was confirmed by repeated temperature logs over a period of 4 days and is not a transient effect. The decrease in gradient is probably too large to be due solely to a change in rock conductivity, although this possibility will be tested by core analyses.

The drilling was terminated because of drilling problems associated with use of BQ diameter tools and safety concerns over the arrival of winter weather. Another exploration well is planned for late 2009 or early 2010 to explore for and determine the productivity of a deeper high-temperature reservoir and perform longer term flow testing.

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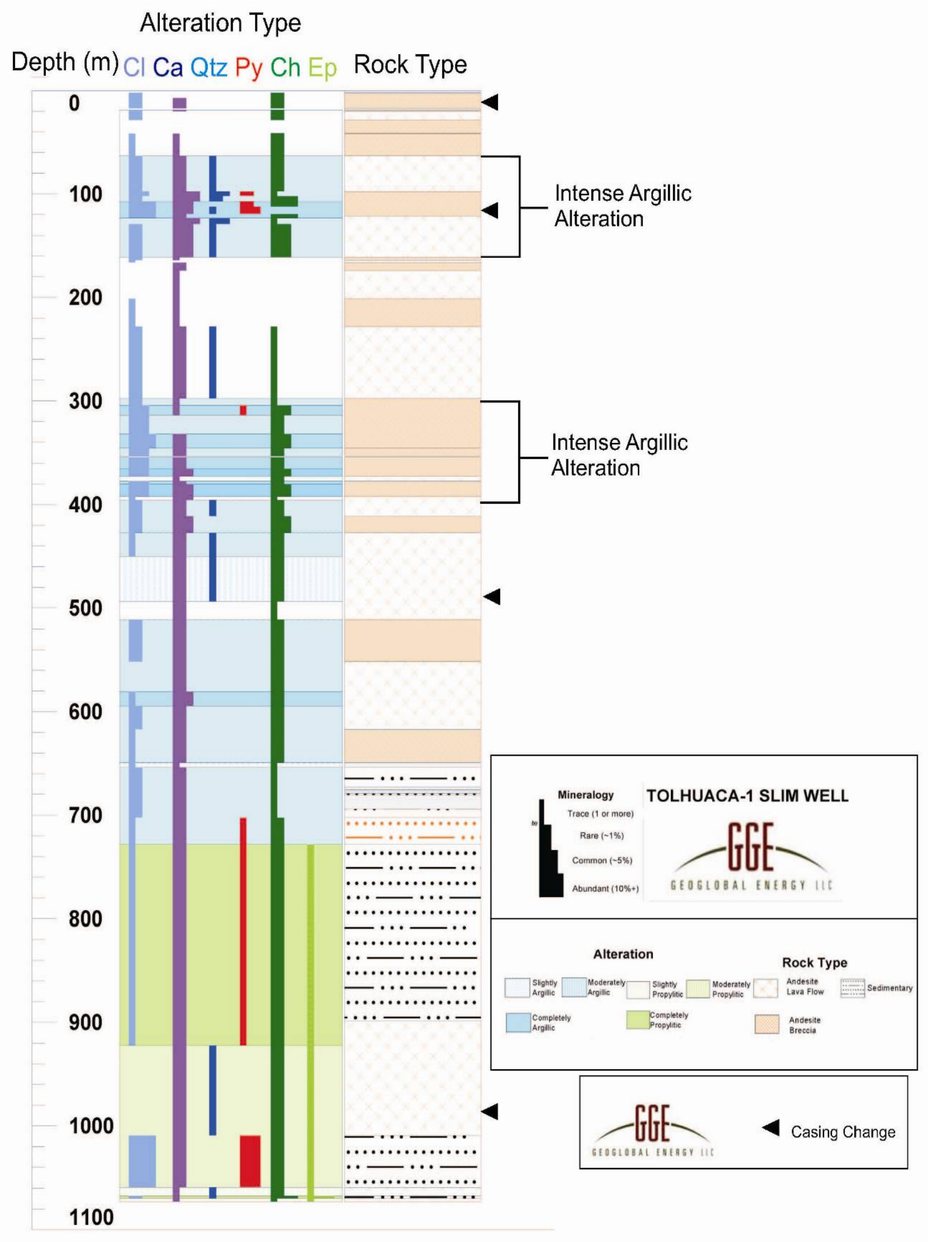

Figure 7. Tolhuaca-1 well geology and alteration

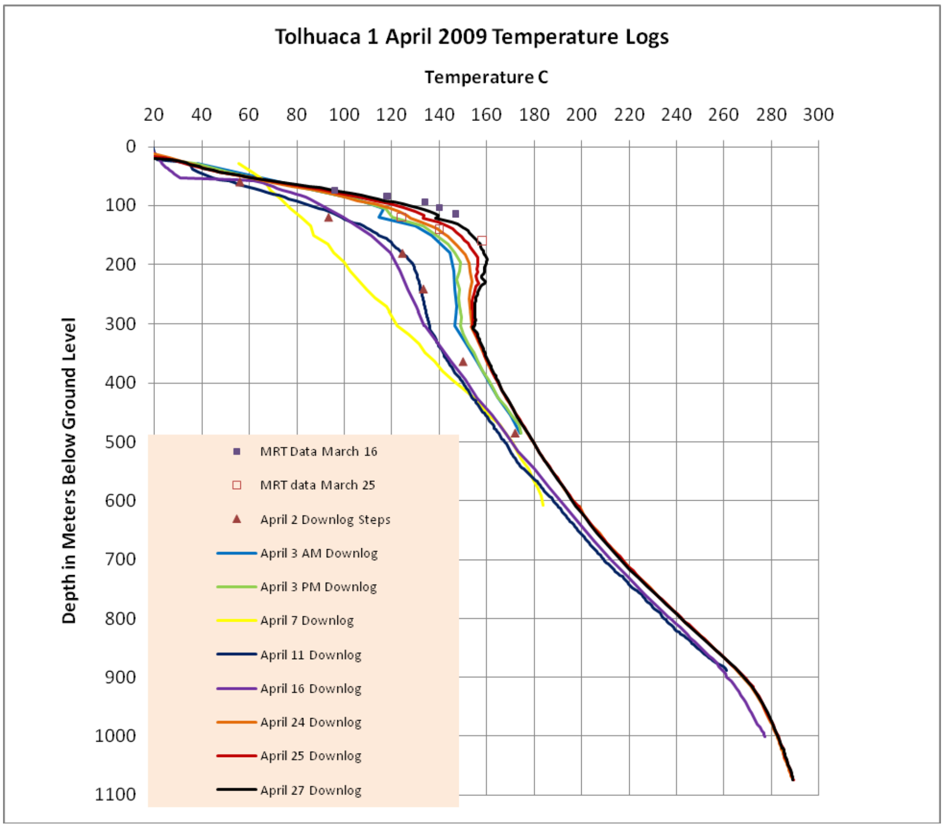

Figure 8. Tolhuaca-1 temperature logs

5. CONCEPTUAL MODEL

The current conceptual model for the Tolhuaca reservoir includes a heat source below the NW flank of Tolhuaca volcano. Deep liquid water upflow supports a ~300ºC reservoir at about 1500 m depth. This reservoir may occur near the contact between interlayered volcanics and sediments and an underlying Tertiary intrusive. Flow rising from this system may undergo boiling and cooling before it reaches the shallow reservoir at about 200 m depth and 160ºC.

6. CONCLUSIONS

Rapid mobilization and near-real-time interpretation of the resistivity, geology and geochemistry surveys supported a timely and ultimately successful move of the drilling target 1.3 km south from the initial, more accessible site.

Flexibility in the plan, equipment, and field crew for the T-MT-AMT allowed adjustment of field operations to lower costs and improve effectiveness by re-focusing on the geothermal target and adjusting for the signal to noise conditions as they were revealed.

The resistivity data show a strong and impressively detailed correlation to the pattern of alteration in the well.

Revisions to the reservoir conceptual model based on detailed surface exploration include indications that the interpreted reservoir temperature is nearly ~300ºC and the steam cap reservoir is lower temperature than was expected in the preliminary model.

Potential for a reservoir >289ºC has been demonstrated with sufficient reliability to justify mobilizing a rig in early 2010 to drill to 1500 m to test the deeper zone.

REFERENCES

Cumming, W., 2009, Geothermal resource conceptual models using surface exploration data. *Proceedings*, 34th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Cumming, W. and Mackie, R. 2009. MT Survey for Resource Assessment and Environmental Mitigation at the Glass Mountain KGRA. *California Energy Commission, GRDA Geothermal Resources Development Account*. PREPRINT 10-2008.

Davatzes, N. and Hickman, S., 2009, Fractures, stress and fluid flow prior to stimulation of well 27-15, Desert Peak, Nevada, EGS Project. *Proceedings*, 34th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Giggenbach, W.F., 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators.*Geochimica et cosmochimica acta*, 52: 2749-2

Gunderson, R., Cumming W., Astra D., and Harvey, C., 2000. Analysis of Smectite Clays in Geothermal Drill cuttings by The Methylene Blue Method for well site geothermometry and resistivity sounding correlation. *Proceedings* World Geothermal Congress 2000. Kyushu – Tohoku, Japan, May 28 – June 10, 2000.

Hauser, A., 1997; Catastro y caracterizacion de las fuentes de aguas minerales y termales de Chile, *SERNAGEOMIN*, Santiago, 1997, p. 77

Hermance, J. and Thayer, R., 1975, The telluric-magnetotelluric method, *Geophysics* 46, 1137-1147.

Melosh, G., 2006, Region IX GDP Geothermal Exploration Project Technical Report, unpublished Geotermia Del Pacifico report, 43 pgs.

Melosh, G., Cumming, W., Sussman, D., Benoit, D., Soto, E., Colvin, A., Wilmarth, M., Winick, J., and Fredes, L., 2009, Rapid Exploration of the Tolhuaca Prospect, Southern Chile, *Geothermal Resources Council*, Reno, Nevada, Oct. 4-7, 2009.

Powell T., 2000. A review of exploration gas geothermometry. *Proceedings* 25th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 24-26.

Powell, T., 2003, Geochemical Evaluation of Hot Spring Waters in the Tolguaca, Sierra Nevada and Sollipulli Exploration Areas, Southern Chile, unpublished Report for Geotermia Del Pacifico, 8 pgs.

Stodt, J., Hohmann, G. and Ting, S., 1981, The telluric-magnetotelluric method in two- and three-dimensional environments, *Geophysics* 48, 1137-1147.

Urquhart, S. and Zonge, K. 1997, Combining CSAMT and MT in difficult exploration environments. *The Leading Edge*, The Society of Exploration Geophysics, April 1997. 383-384.

Ussher, G., Harvey, C., Johnstone, R., Anderson, E., 2000. Understanding the resistivities observed in geothermal systems. *Proceedings* World Geothermal Congress 2000. 1915-1920.