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THE EVOLVING ROLE OF MT IN GEOTHERMAL EXPLORATION AT NEWBERRY VOLCANO, OREGON

Al Waibel[1], Les Beard[2], and Gary Oppliger[3]

[1]Columbia Geoscience, Hillsboro, OR, USA
[2]Zonge International, Tucson, AZ, USA
[3]Zonge International, Reno, NV, USA
e-mail: awaibel@hevanet.com

ABSTRACT

Davenport Newberry has been conducting geothermal exploration on Newberry Volcano in central Oregon since 2005. The primary target of the exploration efforts is the western flank of the volcano, which is underlain by plutons associated with Newberry Volcano, some of which are young enough to retain substantial heat. Currently Davenport is mid-way through an exploration program, conducted in conjunction with the DOE Innovative Exploration Technology (IET) Grant 109 program, and MT surveys are a component of this effort. Integration of the MT results with gravity data, drill hole lithology and LIDAR has provided valuable structural and volcanic development of the volcano. This has significantly changed the understanding as to which areas have higher potential for hosting hydrothermal systems. MT data, usually used for deep geoelectrical investigation, has proved useful for shallow interpretation. Integration of two different MT surveys created a high station density, which allowed us to detect small scale shallow features. In the future, improvements in MT receiver design should permit dense data collection and even more detailed interpretations.

INTRODUCTION

Newberry is a Pleistocene to Holocene large bi-modal volcano with a central caldera structure. It is located in central Oregon near the juncture of three geologic provinces, the Cascade Range, the High Lava Plains portion of the Basin Range and the Blue Mountains. The most recent eruption occurred within the caldera 1350 years ago. Holocene silicic and basaltic volcanism attracted geothermal interest to the volcano by the early 1970s. Holocene silicic and basaltic eruptions on the volcano have attracted interest in its geothermal potential since the late 1960s. High temperature gradients were observed in temperature gradient holes drilled on the upper west flank of the volcano (Oregon Dept. Geol.). This west flank thermal anomaly has no expression at the surface, either active or fossil. It is a true "blind" prospect. These high temperature gradients, however, led to four deep exploration wells being drilled, all on the upper northwestern flank of the volcano (Figure 1). Three of the deep wells encountered high temperatures CEE 23-22, 550^{o}F; CEE 86-21, 600^{o}F; NWG 55-29, >600^{o}F) though little or no flow. The fourth well, NWG 46-16, intersected hydrothermal veins, has a projected bottom-hole temperature of between 630 and 700^{o}F, has a sustained flow of non-condensable gasses leaking upward through a bridge in the well, and has a shut-in well-head pressure of 575 to 600 psi. (Waibel et al., 2012).

Exploration for geothermal drilling targets in a true "blind" geothermal area has its challenges. The two CEE wells targeted hypothesized ring fractures associated with the central caldera. Magnetotelluric survey data were employed initially for investigation of deep structures (more than a few km), but once data from two different data sets were combined, MT eventually became a tool for shallow interpretation as well.

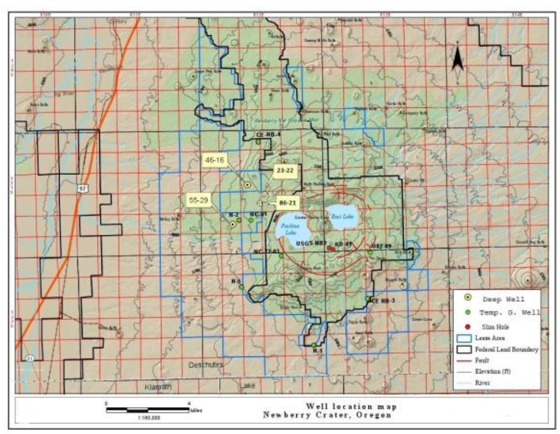

Figure 1: Location map of Newberry Crater with key wells marked.

GEOLOGY

Newberry Volcano is an active broad bi-modal Quaternary volcano with a central caldera that has been active for approximately the last 600,000 years (MacLeod et al., 1995; Jensen, 2006). The oldest lava from Newberry has been dated at 400,000 years. Localized volcanism over a long period of time markedly distinguishes Newberry from the silicic volcanism occurring to the east in the Basin-and-Range portion of Oregon and from the strato-volcanoes of the Cascade Range to the west. Shallow hot granitic plutons underlie a portion of the caldera and extend outward under the west flank of the volcano. Temperature gradient wells on the west flank show a relatively high measured temperature gradient of 6°F-7°F/100 ft. Four deep geothermal exploration wells drilled on the upper northwest flank of the volcano encountered temperatures from 550 to in excess of 600^{o}F in both granitic plutons and in thermal metamorphosed volcanic rock.

Newberry Volcano is located in an area that has been volcanically active since late Eocene time. The volcanic rocks of the John Day formation extend through into the Newberry Volcano area, with major calderas in the Powell Butte and Prineville areas. Sherrod et.al. (2004) describe up to 4,300 meters of rhyolite, basalt, andesite tuffs and related pyroclastic and sedimentary deposits of John Day material in the Bend quadrangle, just to the north of Newberry Volcano. Uncomformably overlying the John Day Formation are basalt flows and silicic volcanic products of the Miocene Mescall Formation. Above the Mescall Formation lie the mafic and silicic volcanic rocks of the Pliocene Deschutes Formation, followed by Pliocene to Recent post-Deschutes lavas, pyroclastic deposits and volcanic sedimentary deposits. Portions of the above formations are projected and reasonably anticipated to underlie the flanks of Newberry Volcano.

GEOPHYSICAL SURVEYS

A variety of different geophysical surveys have been carried out at Newberry volcano. Among these are magnetotellurics, gravity, LIDAR, and geophysical logging.

Magnetotellurics

Magnetotelluric surveys have been one of the more popular geophysical methods used in geothermal exploration because geothermal systems often exhibit electrical resistivity contrasts at depths of several kilometers, a depth accessible to MT but not to other electrical or electromagnetic methods. MT is a passive method, using powerful, naturally-occurring ionospheric current sheets and lightning storms as energy sources. Some of the first MT data collected at Newberry volcano was by the University of Oregon in 1986 (Urquhart, 1988). Modeling based on these MT data were consistent with the area being a potentially important geothermal resource, and led to additional work in the area.

The MT method combines measurements of the earth's electric field and the earth's magnetic field over a wide band of frequencies. Information about the earth's electrical resistivity for a particular frequency can be obtained from a simple ratio of orthogonal electric and magnetic components, for example $|E_y/H_x|$. The depth of investigation is inversely related to the square root of frequency such that low frequencies sample deep into the earth and high frequencies correspond to shallow samples. At Newberry, MT soundings sampled frequencies from 8200 Hz to 0.002 Hz. Given the rock resistivities encountered at Newberry, this implies investigation depths from about 100 m to more than 25 km.

Electrical interference from cultural sources can in most cases be effectively reduced through the use of a remote reference MT station (Gamble et al., 1979). A remote reference receiver was employed at Newberry, and proved effective in reducing interference from a cathodically protected pipeline that ran through the area.

Two MT surveys were conducted on behalf of Davenport Newberry. The first, centered on the western flank north of Paulina Creek, was carried out by Geosystems in 2006. The second, carried out by Zonge in 2011, provided in-fill on the western flank and expanded to the north and south slides of the volcano. Figure 2 shows the combined station locations from both surveys. The main emphasis with the MT processing has been to understand the relationship between the MT, gravity and geology data, and insight into possible structures as indicated by LIDAR.

Gravity

Two gravity surveys were completed under the direction of Davenport Newberry, the first in 2007 and the second in 2010. Both surveys were carried out by Zonge International. Figure 3 shows the complete Bougeur Anomaly with a density value of 2.5 g/cc. Paulina and East Lakes, located within the caldera, are outlined, in addition to the Newberry National Volcanic Monument boundary and Paulina Creek.

The gravity data show the subsurface volcano to be different from the observable topographic edifice. The volcano is located on a structural block with edge trends NNW and ESE. The positive gravity anomaly (magenta in Figure 3) underlying the western flank and portions of the caldera are interpreted as high density plutons. This interpretation is supported by granodiorite encountered in both CEE wells (86-21 and 23-22), and by felsic dikes encountered in well 55-29 (Waibel et.al., 2012). High temperature gradients observed on the upper west flank and high temperatures measured in all four deep exploration wells indicate that at least a portion of the plutons underlying the west flank are young enough to still be hot.

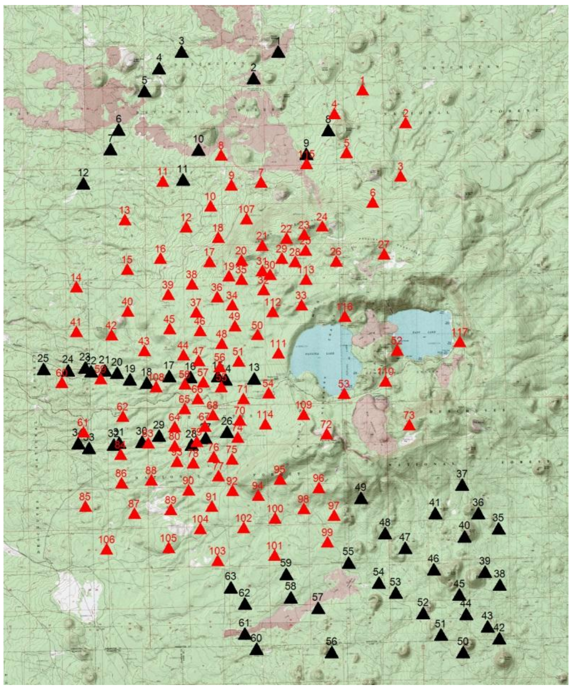

Figure 2: MT station locations at Newberry volcano. Geosystems 2006 MT stations are in red and Zonge 2011 stations are in black. Area is about 25 km x 20 km.

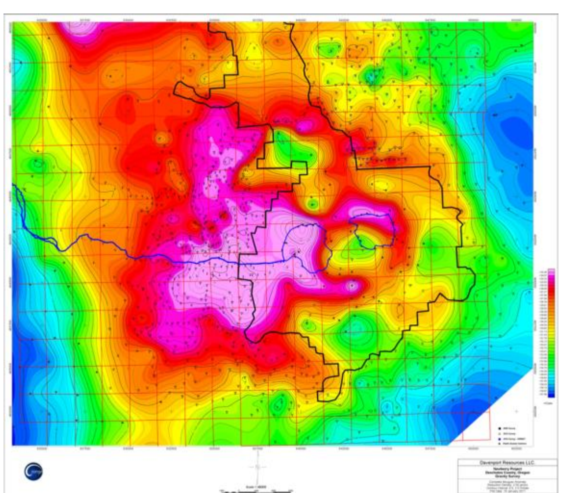

Figure 3: Bouguer gravity anomaly of Newberry volcano. Gravity station locations are shown as well as the National Monument boundary. East Lake, Paulina Lake, and Paulina Creek outlined in blue.

LIDAR

LIDAR imagery of Newberry Volcano became available to Davenport in 2011. The LIDAR imagery allowed the technical team to see details of topographic features that previously were unavailable. The LIDAR imagery has been examined for hints of structural patterns, and has been overlain with geologic maps and geophysical information, looking for possible correlations. There appears to be little if any correlation between the gravity data (Figure 3) and the LIDAR image, shown in Figure 4. The magenta line in Figure 4 identifies a general boundary between the relatively unbroken surface area to the east and the eroded and broken surface areas to the west and north. This line location roughly corresponds with the edge of a highly conductive lens, shown in Figure 5 and denoted "edge." Without ground truth, it is difficult to draw any solid conclusions from these observations.

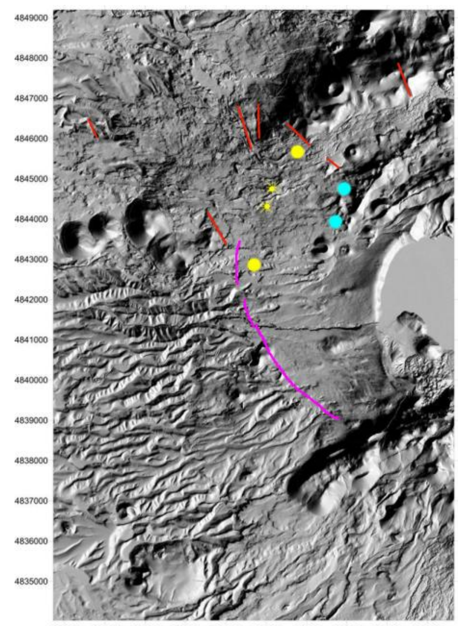

Figure 4: LIDAR image of the west flank of Newberry Volcano. The yellow dots mark Davenport deep exploration well 46-16 (north) and 55-29 (south). The blue dots mark the CalEnergy deep exploration well 23-22 (north) and 86-21 (south). The yellow asterisks marks the locations of recently recorded small earthquakes. The magenta line marks the arcuate boundary between predominantly unbroken surface area to the east and the more broken surface areas to the west and north. The red lines identify a few of the linear patterns, some of which may reflect surface breakage associated with deeper strain.

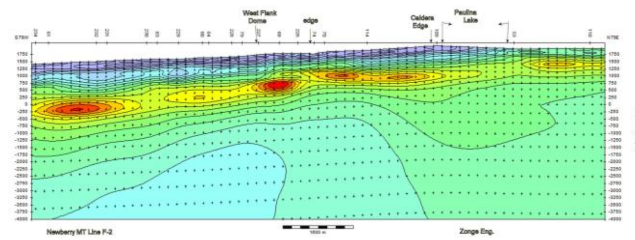

Figure 5: Line F (position shown in Fig 8). The location marked "edge" near the center of the line denotes the LIDAR boundary between smooth and broken terrain.

WELL LOGS

To date four deep exploration test wells have been completed on the upper northwestern flank of Newberry Volcano, CEE 23-22, CEE 86-2 1, NGC 46-16 and NGC 55-29. Well 23-22 intersected a granodiorite intrusion at 8,780 ft., and continued in the granodiorite to a depth of 9,602 ft. The well had a reported bottom-hole temperature of 550^{0}F. Well 86-2 1 intersected a section of intrusive dikes and contact metamorphosed volcanic rocks at a depth of 8,200 feet, and into granodiorite at a depth of 8,700 feet. The well had a reported bottom-hole temperature of 600^{o}F. Well 55-29 encountered greenschist facies metamorphosed volcanic rock by 6,400 feet. Below 7,500 feet both silicic and basaltic subvolcanic dikes were encountered. The well has a measured bottom hole temperature of more than 600^{o}F. Well 46-16, drilled approximately 1 mile WNW of well 23-22, encountered thermally metamorphosed volcanic rock to a drilled depth of 11,600 ft., and had an estimated bottom-hole temperature of between 600 and 700^{o}F.

Figure 6 displays the gamma logs for the four deep exploration wells. Higher gamma readings indicate higher K, Th and U content within the rock, corresponding to more silicic volcanic rock. Low gamma readings indicate low K, Th and U content within the rock, corresponding to low silica, or more basic volcanic rock. Unfortunately two wells, CEE 86-21 and CEE 23-22, do not have complete gamma logs available. The gamma logs show an absence of any stratigraphic correlation between the wells, using only silicic verses mafic composition. A lack of stratigraphic correlation in the upper few thousand feet might be dismissed as the vagaries of young volcanoes. The lack or correlation in the deeper sections, where the wells should have intersected Pliocene and Miocene formations poses a more difficult problem. No surface or down-hole evidence for fault off-sets between the holes is observed. It is proposed by the authors that volcanic eruption and collapse craters on the west flank, now obscured by subsequent eruption material from within the current caldera, could account for the lack of deep lithology correlation.

MT Results

Magnetotelluric data were collected by Zonge International in the summer of 2011. The survey was designed such that where possible, data were collected along extended lines for 2D inversion. Also, locations were chosen so that data could be integrated with a previous MT survey conducted in 2006 by Geosystems. No MT data could be collected in the present caldera itself because it is a protected national monument, therefore all Zonge MT lines were located on the flanks of the volcano.

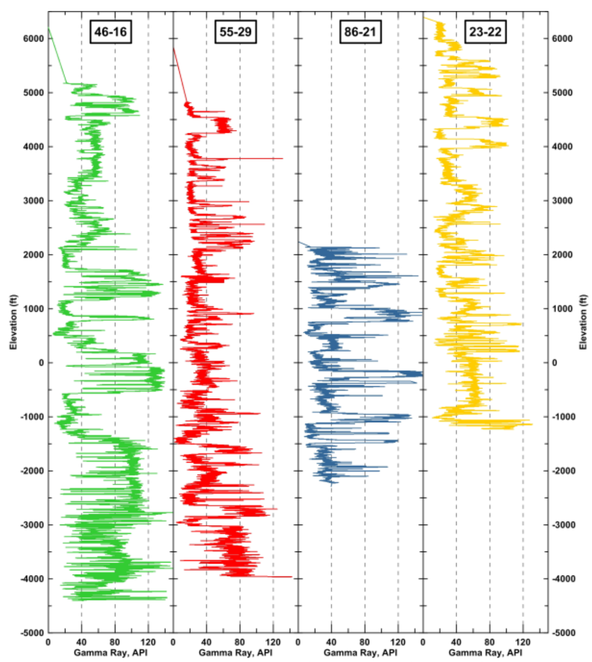

Figure 6: Gamma logs of each of the four deep exploration wells drilled on the northwest flank of Newberry Volcano.

Results from the Zonge survey were broadly consistent with a University of Oregon survey (Urquhart, 1988) and the 2006 Geosystems survey. On the flanks of the volcano, 1-D inversions of the MT data consistently imaged three principal geoelectrical units. Figure 7 shows 1-D Bostick inversions of a line of four stations on the south flank of the volcano. Bear in mind that in this context, the term "layer" is used loosely to describe 1D inversion results beneath a station, but does not imply horizontal, flat-lying layers on a larger scale. As can be seen in the 2D inversions shown, each of the three layers varies in thickness and resistivity. The top layer is resistive, with resistivities on the order of 1000s of ohm-m, and has a thickness of about 1 kilometer. The layer below this is relatively conductive, about 10 ohm-m, and with a thickness of about 2 km. Below this, a more resistive layer of about 100 ohm-m replaces the conductive layer. This modestly resistive third layer may have a thickness of several kilometers.

The interpretation of the resistive geoelectrical top layer is that it consists of volcanic rubble or dense flows. Because of low rock porosity in some units and a deep water table this upper unit is undersaturated to completely dry, and this can produce high electrical resistivity. The relative absence of water also slows weathering and alteration to more conductive clays. The conductive second layer was similar to the top layer, but has been altered by hot fluids to smectite-family clays. These clays, and the fact that the second layer is mostly below the water table, combine to produce a layer with low resistivities, usually in the tens of ohm-m, but sometimes lower. Both of the top two layers have been well-sampled by boreholes, and borehole results support this interpretation.

The third layer is an order of magnitude or more resistive than the conductive second layer. In large part this is probably caused by a different style alteration at higher temperatures, from the smectite-family clays to a smectite-illite or chlorite assemblage. These phases have been shown to increase bulk resistivity (Pearson, 1987). Higher resistivities may also be caused by lower porosity in deeper layers caused by increased lithostatic pressure. Furthermore, one of the few deep drill holes in the area, well 23-22, encountered granodiorite, indicating that not all the rocks at Newberry are volcanic.

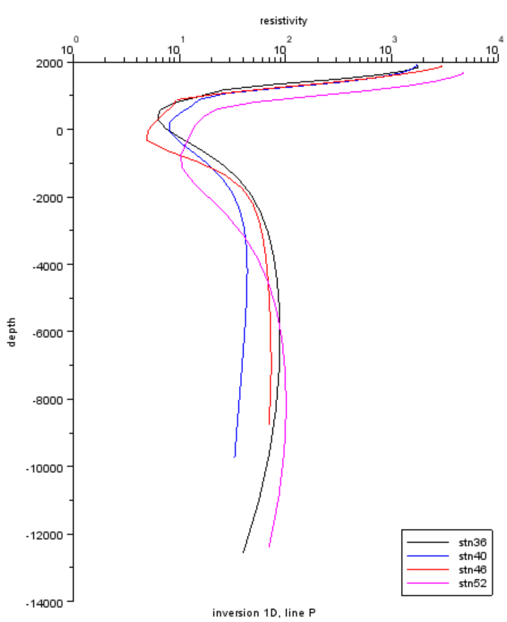

Figure 7: 1D Bostick inversions of four MT stations on the south flank of Newberry volcano.

Figure 8 shows the locations of a few selected lines of MT stations that were chosen for inversion. MT Line D, shown in Figure 9, intersects both well 46-16 and the north-northwest volcanic vent trend. Well 46-16 is shown to be located between two intense alteration lenses, with vertical off-set suggested by the geometry of the variations in intensity of the electrical conductor. The north-northwest volcanic vent trend which is a major surface feature, made up of a pattern of multiple basalt volcanic vents dating to about 7,000 years ago, does not stand out as a geologic variable affecting the electrical conductivity.

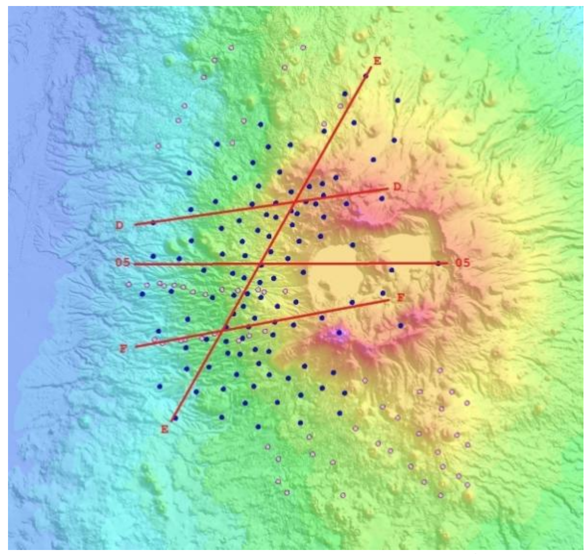

Figure 8: MT station locations and four lines selected for inversion.

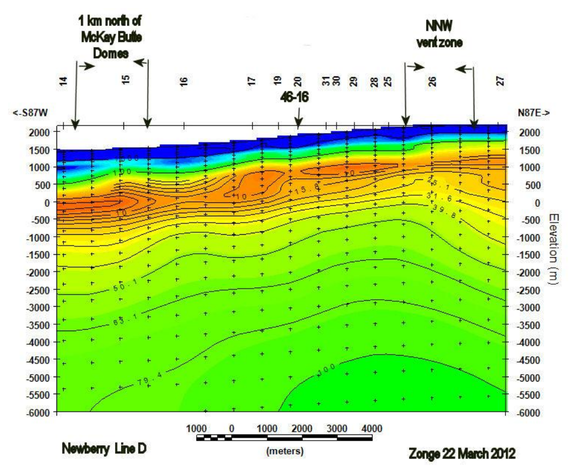

Figure 9: Resistivity cross-section along Line D in Figure 7.

The resistivity cross-section for MT Line E, shown Figure 10, strikes NNE, and intersects wells 55-29, 46-16 and the north-northwest volcanic vent zone. On this line well 55-29 is shown to be located within a lens of particularly intense low temperature clay alteration as depicted by the very low electrical resistivity. This alteration, as identified on the MT slice, begins at a depth of about 400 m (1300 ft.), and transitions toward the lower electrical conductive greenschist facies alteration at a depth of about 2,200 m (6,400 ft.). This agrees with the mineralogy observed in the well cuttings from well 55-29. Well 46-16 is shown located outside of the intense clay alteration lenses. The north-northwest volcanic vent trend is not recognized in this MT slice, though the MT stations spacing is quite wide at this point and may not have been able to identify any shallow perturbations. This figure does show a marked variation in the subsurface character of the volcano from the west flank and the northern flank. The western flank shows a relatively compact shallow conductive layer. The northern flank shows a sloping, ever deepening higher electrical resistivity boundary. This difference may be related to the plutons (Figure 3) and associated eruptive history of the west flank that is not present under the northern flank. As with Line D above, the NNW volcanic vent zone is not identified in Line E by any variation in electrical resistivity.

At first glance, the conductive second layer from the Newberry MT surveys appears similar the "mushroom" model, which assumes rocks have been altered to conductive clays by upwelling geothermal fluids. Indeed, this model may well be valid for places like Indonesia (Raharjo et al., 2002), but Newberry poses difficulties for the model. Evidence of current large scale (>1km across at >1.5km depth) geothermal fluid circulation cells has not been observed in any of the data. However, the temperatures range required to cause smectite alteration is low enough, and the temperature gradient at Newberry high enough that the conductive blanket could have been caused by warm in-situ fluids without recourse to massive upwelling. Figure 11 shows geothermal wells drilled on the west flank of the volcano with temperatures in the range 70-200°C, which would likely be in the stability range for smectites and other clay minerals (Ussher et al., 2000).

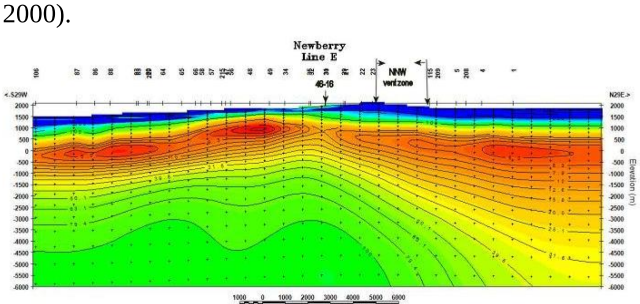

Figure 10: Resistivity cross-section along Line E in Figure 8.

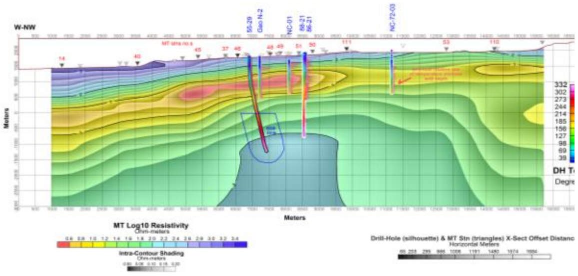

Figure 11: Resistivity cross-section along a line extending WNW to ESE from the west flank of Newberry volcano across Paulina Lake. Refer to Figure 2 for station locations.

DISCUSSION AND RECOMMENDATIONS

The relationship between geothermal systems and hydrothermal ore deposits has been recognized for well over a century (i.e. Becker, 1888). During the subsequent decades a plethora of information has been published regarding the structural and hydrological dynamics of the formation of ore bodies, four-dimensional reconstructions of the hydrothermal activity associated with the deposition of economic and sub-economic ore bodies. A review of some of these data (i.e. Becker, 1888; Begbie et.al., 2007; Berger and Bethke, 1985; Boyle, 1979; Camus et.al., 1991; Casadevall and Ohmoto, 1977; Cathless et.al., 1997; Gruen et.al., 2010; Kloppenburg et.al., 2010; Landtwig et.al., 2010; Lund et.al., 2011; Musgrave and Thompson, 1991; Otto et.al., 2009; Raines et.al., 1991; Rowland and Simmons, 2012; Sibson, 1987; Sillitoe, 2010; Vey et.al., 2010; Willis and Tosdal, 1992) identifies three general site associations for the occurrence of geothermal activity located in volcanic terrain; porphyry pluton stockwork, fractured subvolcanic rock and structural dilation. The porphyry system (Figure 12) occurs in highly fractured portions of some felsic plutons and typically at depth is measured in square kilometers (i.e. Kloppenburg et.al., 2010; Vey et.al., 2010). Fractured subvolcanic rock, particularly dikes (Figure 13), can host geothermal systems and are usually measured in hundreds of meters across rather than kilometers (i.e. Camus et al., 1991; Fisher, 1990). Dilation zones along regional structures within volcanic terrain (Figure 14) also are recognized hosts of epithermal geothermal systems (i.e. Camus et.al., 1991; Otto et.al., 2009) and are typically measured in hundreds of meters across at depth. While occurring in volcanic terrain, the dilated structures are akin to geothermal cells in non-volcanic extensional terrain such as the Basin and Range (Blackwell et al., 2012). MT as an exploration tool for geothermal resources is able to readily identify hydrothermal activity associated with porphyry-like systems due to the larger-scale geometry of these systems. MT is not able to resolve the subvolcanic- and structural dilation-hosted geothermal cells at depths of 2 to 3 km due to their limited size, particularly with the smoothing affects in 3-D modeling. Close-spaced MT arrays can, however, provide valuable information for identifying shallower structure that contributes significantly to the exploration program. The integrated model for the west flank of Newberry Volcano suggests that the shallow electrically conductive lenses (Figures 9, 10 and 11) are associated with increased clay alteration of volcaniclastic rubble in earlier eruptive craters rather than with clay alteration associated with discharging geothermal fluid. These craters are volcanic structures associated with plutons now located under the western flank of the volcano. Wells Geo N-2 and 55-29 drilled through one of the shallow conductive lenses (Figure 10). The deeper well 55-29 encountered a variety of volcanic and volcaniclastic rock, progressively increasing in thermal metamorphic grade. While fractures were observed in the brittle deeper epidote-greenschist facies, they all appear to have been isolated.

The hydrothermal fractures observed in well 46-16 are hosted in contact metamorphosed volcanic and volcaniclastic rock. This is the only well that did not intersect intrusive rock. The fractures were limited in vertical extent to two zones, with no associated change in the metamorphic grade. This indicates that the geothermal fractures are likely associated with a vertical permeability dilation structure. The Permeable fractures hosting geothermal fluid were not observed by the MT data because there was no change in the metamorphic mineral assemblage between the fracture area and the surrounding rock, and the geometry of the geothermal fractures is likely too limited for surface-based MT surveys to identify at 3 km depth.

The discussion above points to challenges in obtaining the best MT results for a particular geothermal exploration. Clearly it is not a case of "one size fits all." Shallow features may not be well defined if station spacing is too large, and small features at depth will always be difficult to image adequately because of low resolution from deeply penetrating low frequencies. At Newberry, CSAMT could have provided excellent shallow resolution, but we were unable to obtain permission to use an active high-current transmitter on government property. However, this is not always the case, and where permitted, CSAMT can be acquired with greater station density than MT and provide greater near-surface resolution to depths of about 3km. For greater depth of investigation with geoelectrical methods, MT is required, and new instrumentation is making possible much more dense station coverage at or below the cost of "standard" MT surveys. In addition, these instruments will become flexible enough to be used in a variety of survey methods, making it possible to design surveys that collect electromagnetic/electrical data both active and passive sources. Such data sets will permit resolution in considerably greater detail than MT-only surveys.

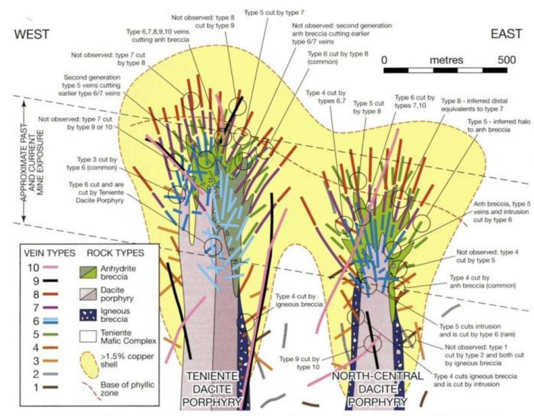

Figure 12: Complex 3-D fracture system associated with porphyry-type hydrothermal systems (from Vey et al., 2010).

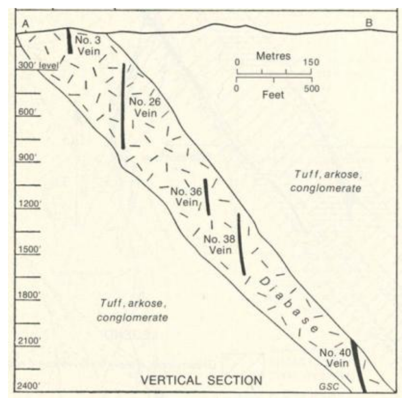

Figure 13: Hydrothermal vein location in a subvolcanic dike (from Boyle, 1979, p 256).

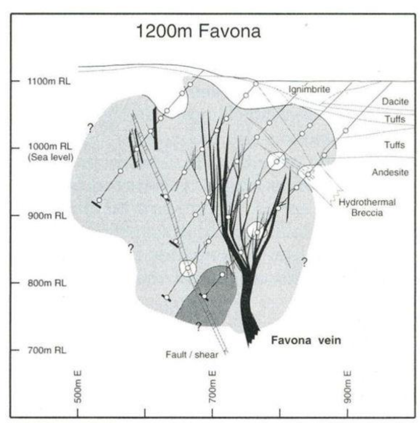

Figure 14: Geometry of a dilated fracture-hosted epithermal deposit in volcanic terrain (from Simpson and Mauk, 2007).

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REFERENCES

Becker, George F., 1888, Geology of the quicksilver deposits of the Pacific slope. U.S. Geol. Survey Monograph XIII, Washington, Government Printing Office, 486 pp., with Atlas.

Begbie, Michael J., K. Bernhard Sporli and Jeffery L. Mauk, 2007, Structural evolution of the Golden Cross epithermal Au-Ag deposit, New Zealand. Economic Geology, Vol. 102, No. 5, pp. 873-892.

Berger, B.R. and P.M. Bethke, eds., 1985, Geology and geochemistry of epithermal systems. Reviews in Economic Geology, Vol. 2, Society of Economic Geologists, 298 pp.

Blackwell, D., A.F. Waibel and M. Richards, 2012, Why Basin and Range geothermal systems are hard to find: The moral of the story. in: Geothermal Resources Council Trans. Vol. 36, pp. 1321-1326.

Boyle, R.W., 1979, The geochemistry of gold and its deposits. Geol. Survey if Canada Bull. 280, 584 pp.

Camus, Francisco, Ricardo Boric, Milka Alexandra Skewes, Juan Carlos Castelli, Enrique Reichhard and Andres Mestre, 1991, Geologic, structural, and fluid inclusion studies of El Bronce epithermal vein system, Petorca, central Chile. Econ. Geol., Vol. 86, no.6, pp. 1317-1345.

Casadevall, Tom and Hiroshi Ohmoto, 1977, Sunnyside Mine, Eurika Mining District, San Juan County, Colorado: Geochemistry of gold and base metal ore deposition in a volcanic environment. Econ. Geol., Vol. 72, no. 7, pp. 1285-1320.

Cathless, L.M, A.H.J. Erendi and T. Barrie, 1997, How long can a hydrothermal system be sustained by a single intrusive event? Economic Geology, Vol. 92, No. 7/8, pp. 766-771.

Fisher, Frederick S., 1990, Gold deposits in the Sneffels-Telluride and Camp Bird Mining Districts, San Juan Mountains, Colorado. *in:* Gold-bearing polymetallic veins and replacement deposit - Part II, U.S.G.S. Bull. 1857-F, pp. F12-F18.

Gamble, T.D., W.M. Gaubau, and J. Clarke, 1979, Magnetotellurics with remote magnetic reference: Geophysics, vol. 79, pp 53-68.

Gruen, Gillian, Christoph A. Heinrich and Kim Schroeder, 2010, The Bingham porphyry Cu-Mo-Au deposit. II. Vein geometry and ore shell formation by pressure-driven rock extension. Econ. Geol., Vol. 105, No. 1, pp. 69-90.

Jensen, Robert A., 2006, Roadside guide to the geology of Newberry Volcano. *Fourth edition* CenOreGeoPub, Bend, Oregon, 182 pp.

Kloppenburg, Armelle, John Grocott and David Hutchison, 2010, Structural setting and synplutonic fault kinematics of a Cordilleran Cu-Au-Mo porphyry mineralization system, Bingham Mining District, Utah. Economic Geology, Vol.105, No.4, pp. 743-761.

Landtwing, Marianne R., Caroline Furrer, Patrick B. Redmond, Thomas Pettke, Marcel Guillong and`Christoph A. Heinrich, 2010, The Bingham Canyon porphyry Cu-Mo-Au deposit. III. Zoned copper-gold ore deposition by magmatic vapor expansion. Econ. Geol., Vol. 105, No. 1, pp. 91-118.

Lund, K, R.G. Tysdal, K.V. Evans, M.J. Kunk and R.M. Pillers, 2011, Structural controls and evolution of gold-, silver-, and REE-bearing copper-cobalt ore deposits, Blackbird District, east-central Idaho: Epigenetic origins. Economic Geology, Vol.106, No.4, pp. 585-618.

MacLeod, N.S., D.R. Sherrod L.A. Chitwood and R.A. Jensen, 1995, Geologic map of Newberry Volcano, Deschutes, Klamath, and Lake Counties, Oregon. U.S. Geological Survey Misc. Geologic Investigations Map I-2455.

Musgrave, John A. and Tommy B. Thompson, 1991, Sultan Mountain Mine, western San Juan Mountaons, Colorado: A fluid inclusion and stable isotope study. Econ. Geol., Vol. 86, no.4, pp. 768-779.

Oregon Department of Geology and Mineral Industries electronic geothermal data base.

Otto, Bruce R., Joe Pieknbrock and John Odden, 2009, Structural evolution of the Rock Creek Gold Deposit, Seward Peninsula, Alaska. Economic Geology, Vol.104, No.7, pp. 945-960.

Pearson, C., 1987, Effect of clay minerals on the resistivity of geothermal rocks: EOS, 68, 470.

Raharjo, I., P. Wannamaker, R. Allis, and D. Chapman, 2002, Proceedings of the 27th Workshop on Geothermal Reservoir Engineering, 7 pp.

Raines, Gary L., Richard E. Lisle, Robert W. Schafer and William H. Wilkinson, eds., 1991, Geology and ore deposits of the Great Basin, Symposium Proceedings. Geological Society of Nevada, 1257 pp.

Rowland, Julie V. and Stewart F. Simmons, 2012, Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits. Economic Geology, Vol. 107, No, 3, pp. 427-457.

Sherrod, David R., Edward M. Taylor, Mark L. Ferns, William E. Scott, Richard M. Conrey, and Gary A. Smith, 2004, Geologic map of the Bend 30-x60-minute quadrangle, central Oregon, U.S. Geological Survey Geologic Investigations Series I-2683.

Sibson, Richard H., 1987, Earthquake rupturing as a mineralizing agent in hydrothermal systems. Geology, Vol. 15, No. 8, pp. 701-704.

Sillitoe, Richard H., 2010, Porphyry copper systems. Economic Geology, Vol.105, No.1, pp. 3-41.

Simpson, Mark P. and Jeffery L. Mauk, 2007, The Favona epithermal gold-silver deposit, Waihi, New Zealand. Economic Geology, Vol. 102, pp. 817-830

Urquhart, S.A., 1988, A magnetotelluric investigation of Newberry Volcano, Oregon: University of Oregon Master’s thesis, 75pp.

Ussher, G., C. Harvey, R. Johnstone, and E. Anderson, 2000, Understanding the resistivities observed geothermal systems: Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, pp. 1915-1920.

Vey, V.H., J. J. Wilkinson, J. Seguel and J. Millan, 2010, Multistage intrusion, brecciation, and veining at El Teniente, Chile: Evolution of a nested porphyry system. Econ. Geol., Vol. 105, No. 1, pp. 119-153.

Waibel, Albert F., Zachary Frone and Todd Jaffe, 2012, Geothermal exploration at Newberry Volcano, central Oregon. Geothermal Resources Transactions, Vol. 36, pp. 803-810.

Willis, G.F. and Richard M. Tosdal, 1992, Formation of gold veins and breccias during dextral strike-slip faulting in the Mesquite District, California. Econ. Geol., Vol. 87, No. 8, pp. 2002-2022.